Virtual Underground Training Environment

Jakub Jastrzębski

School of Engineering

Master's thesis

Espoo 26.11.2018

Supervisor

Prof. Mikael Rinne

Advisors

Ph.D. Lauri Uotinen

MSc Ritesh Mishra

Aalto University
School of Engineering

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi
Abstract of the master's thesis

Author Jakub Jastrzębski		
Title Virtual Underground Training Environment		
Master programme European Mining, Minerals and Environmental Programme		
Major European Mining Course		**Code of major** ENG3077
Supervisor Prof. Mikael Rinne		
Advisors Ph.D. Lauri Uotinen, MSc Ritesh Mishra		
Date 01.09.2018	**Number of pages** 106	**Language** English

Abstract

The thesis investigated the feasibility of replacing the classical approach to teaching rock wall mapping with a virtual reality system. The conducted research consisted of user trials conducted with help of over thirty students and employees of the Aalto University staff. The obtained results have found that the VUTE VR system was capable of providing substantial time savings while enabling its users to obtain measurement results of higher quality than those gathered in real-life and in result proving that for teaching purposes, the system is a feasible replacement to the real-life tunnel visit

Keywords VR, virtual reality, mining, education, rock wall mapping

Page left intentionally blank

Table of Contents

List of figures

List of tables

Abbreviations

CPU – Central Processing Unit

FPS – Frames Per Second or First Person Shooter

GPU – Graphics Processing Unit

UI – User Interface

PPI – Pixels Per Inch

SUS – System Usability Scale

VR – Virtual Reality

1. Introduction

Virtual reality is a concept of generating an immersive illusion of an artificial scene by stimulating mainly the visual and auditory senses. The idea dates back to the late 1950s with first crude simulators being created in 1970s (Kalawsky, 1993). However, it wasn't until 2016 that with the release of the HTC Vive and Oculus Rift headsets the virtual reality has been made available to the public. The now-affordable entry cost counted in hundreds of dollars instead of tens or hundreds of thousands enabled many researchers to study the potential of VR extending beyond just entertainment. The capability of VR to easily generate high quality, immersive, fully interactable 3D scenes and objects has inspired researchers to try and replace the activities cumbersome and/or expensive to organize in real life, such as surgical training, with their virtual counterparts. Various studies dealing with learning applications of the systems have focused on subjects ranging from molecular chemistry (Krupakar, 2017), through military tactics (Stone, 2017) and electric engineering (Valdez et al., 2015). One of the prime examples of an industry, that due to its hazardous operating conditions that make even training potentially unsafe, might greatly benefit from this new technology is mining. Therefore, the author decided to conduct a study that would assess the feasibility of shifting some of the learning activities related to mining engineering from the real world to virtual reality.

One of the unique element of studies at the Department of Civil Engineering of the Aalto University is the practical exercises taking place in the Aalto Underground Research Laboratory tunnels, underneath the main campus in Otaniemi. The exercises are aimed to teach the participating students the fundamentals of tunnel wall mapping for rock mass classification purposes. The classes consist of theoretical lectures taking place in regular classrooms, followed by a visit to the underground Research Laboratory during which students cooperate in teams of two or three, analyzing a selected area. It is without a doubt that the exercises add a significant educational value to the otherwise mostly theoretical classes; however, because to specific conditions within the underground environment, a series of problems arise that strongly limit their potential.

Due to safety reasons, only a limited number of students can be present on site at once. Additionally, several supervisors must be designated to oversee the visit. This results in a significant amount of the teaching staff's time being dedicated to an activity only a limited number of students benefit from.

Moreover, restricted accessibility of the tunnel results in a lack of flexibility when scheduling the classes and the set duration of the exercise, which limits the learning potential.

The author believes that the use of the VR learning environment can provide the same quality learning to the students in a controlled environment, while at the same time eliminating the scheduling issues and enabling its users to tailor the duration of the exercise to their personal needs. Additionally, each visit in the tunnel requires a fixed set of activities connected with reaching the teaching spot, gearing up, safety briefings etc. which significantly limit the time actually spent on the exercises. The VR environment is capable of significantly reducing this time, maximizing the time spent on learning and practicing. Furthermore, the decision on which section of the tunnel might be used for the exercises is often imposed by the roof/wall stability, support condition, tunnel ventilation and carried out works. In result, the actual location where the exercises take place is chosen based on the availability rather than on its learning potential. When utilizing the virtual reality together with the 3D scanning technology, every place in the tunnel that was modeled would be available from nearly anywhere in the world, indefinitely.

The VUTE thesis was the part of MIEDU – Mining Education and Virtual Underground Rock Laboratory – the project aiming to digitize educational resources of the Aalto University and utilizing them for educational purposes with the use of the VR technology.

1.1. The scope of the study

The thesis project was divided into two sections. The first one was focused on the development of the VUTE virtual reality learning software together with the creation of a 3D scan of a rock formation with use of Structure from Motion (SfM) photogrammetric techniques. The second part included testing the system with help of volunteers to assess the benefits it is providing when used for learning purposes, followed by reporting of thereof.

1.2. The aim of the study and stated research questions

In theory, the VR technology is applicable for many diversified uses and capable of providing a range of benefits. Therefore, the author has decided to investigate the potential application of the virtual reality for the mining industry. The main goal of the study was to verify whether it is possible to develop a VR system that would be a feasible replacement of the traditional way that the rock wall mapping is taught at the Aalto University. To do that, a list of four categories related to learning in virtual reality was distinguished for testing purposes.

Those included: the effectiveness and efficiency of learning through VR, the realism of the system, as well as its usability and learnability. In relation to each of the categories a research question was stated:

1. Is the effectiveness of learning through virtual reality better than through real-world tunnel visit? If yes, then by how much?
2. For teaching purpose, is the use of the VR environment more efficient than the actual visit to an underground tunnel? If yes, then by how much?
3. What are the main differences between the VR experience and the real-world tunnel visit?
4. Is the designed Virtual Underground Training Environment system usable and learnable?

Based on the first two questions a first testable hypothesis was assessed, related to the quality and efficiency of learning with the use of the created VUTE system. The hypothesis stated that:

The developed virtual reality software reduces the time spent on the rock wall mapping exercise while maintaining the same or better learning outcomes as the real tunnel visit

Furthermore, the third and fourth research questions were used to formulate the second hypothesis focusing on the design of the system, namely its quality and consistency with the real-life. The second hypothesis stated that:

The created VUTE system is free from significant issues and replicates the real-life tunnel visit in a way that allows for their direct comparison

The following thesis will be dedicated to verifying the two hypotheses based on the data provided by the study.

1.3. Methodology

The development of the VUTE system included the development of the VR environment within a 3D engine of a proven quality, to be able to run it with use of readily available VR headset. As the main element of the VR environment a 3D scan of an existing section of a rock wall was created with the use of photogrammetry - low cost and high-fidelity 3D scanning technique proved to be capable of capturing sub-millimeter details. With help of 20 volunteers from the Aalto University, the system was then tested against the real visit to the underground tunnel. The correctness of the rock wall measurements was assessed using a grading system developed for the use in this study.

The usability and learnability of the system were assessed using the System Usability Scale – the standard tool used in usability engineering. The direct way of testing the differences between the real-life and the VR using the comparison of length estimations in both settings was suggested, together with SUS, by Lauri Malmi – professor of Department of Computer Science of Aalto University. The design of the VR and real-life tunnel exercises was created with help of Jussi Leveinen – professor of Department of Civil Engineering of Aalto University.

1.4. Structure of the thesis

The following thesis is divided into seven main chapters:

- Chapter 1. Introduction – contains an overview of the thesis, its goals, the applied methodology used to meet those, and the structure of it;
- Chapter 2. Background – reports the findings of the literature study on the current application of VR for mining uses;
- Chapter 3. Development of the VUTE – focuses on reporting the process leading to the selection of hardware necessary to run the virtual reality software and description of the whole process of developing the VUTE software;
- Chapter 4. VUTE feasibility study – describes the design and realization of the series of two user tests of the software;
- Chapter 5. Results of VUTE feasibility study – showcases the results obtained during the VUTE tests;
- Chapter 6. Discussion of results and conclusions – contains an analysis of the experimental data and subsequent conclusions;
- Chapter 7. Recommendations and path forward – focuses on the recommendations of the author for a future research and lists several advises that can be leveraged when creating a similar VR system.

2. Background

The goal of the background study was to synthesize the already existing knowledge related to application of the Virtual Reality technology in mining industry, more precisely in training related activities. This has been done in two steps: first through search for relevant literature and later by describing and summarizing the findings.

2.1. Database literature search

The search was conducted with use of the ScienceDirect, database containing scientific publications from 2.5 thousand journals and 33 thousand books (ScienceDirect, 2018) and Scopus, database covering over 21 thousand journals and 7.7 million conference papers (Szydlowska, 2016). For a paper to be included in the further evaluation, all three criteria had to be met: subject had to concern mining industry, focus on virtual reality and be published after 2016. The first two criteria are self-explanatory. The last one was stated to ensure that the listed documents contain studies which focus only on the virtual reality in today's meaning – fully 3D, immersive and rendered in high resolution using a VR headset capable of tracking head movement and rotation. Therefore, to ensure that this criterium is met, 2014 was used, the year when the Oculus Rift Development Kit, the first modern VR headset was released.

The ScienceDirect and Scopus databases were searched using the same phrase: $mining\ AND\ "virtual\ reality"$. The logical operator "AND" ensured that the results will include only documents containing both phrases. Moreover, the results were limited to those published in 2016 and later. In the next step, each of the documents listed by the databases in response to the query were reviewed by the author for relevance with the subject and either included in the further study or discarded. The resulting number of research papers is shown in Table 1.

Table 1 Results of the ScienceDirect and Scopus database search with a phrase $mining\ AND\ "virtual\ reality"$

Database	**Number of found documents**	**Number of documents found to be relevant to the subject**
ScienceDirect	698	3
Scopus	285	2

2.2. Google literature search

Considering the extremely low number of the papers relevant to the subject of the thesis and the fact that some of the applications of VR in mining might have been developed but not described in a scientific paper, the author decided to conduct broader search using the Google search engine. The used search phrase $mining\ AND$ "$virtual\ reality$" with a date range set from 2014 to 2018. In result only four additional examples of applying VR in mining have been found.

2.3. Summary of found papers

The first reviewed usage of VR, found using the Google search engine, was the glückauf! project by Realities.io. The idea of mixing the VR technology with 3D scanning to preserve places and make them explorable indefinitely was used to turn the Prosper Haniel, last German underground, coal mine which will close with the end of 2018, into a virtual museum (Capturingreality, 2018). Similar project was developed at the University of New South Vales in Australia. The Mineral Awareness VR experience was a virtual tour of mine sites was developed for smartphone-based headsets to promote the mining industry among the students of the university (Tibbett, 2016).

The HxGN MinePlan 3D was the first example of a serious application of the VR technology in mining. Developed by Hexagon Mining, the software is a professional tool for mine planning and production scheduling, which introduced in June 2017 an option to display the created mine layouts in full 3D using the HTC Vive headset and controllers (Hexagon, 2017). The first found professional VR training software was developed by MacLean engineering and utilizes smartphone headsets together with gesture recognition sensor to help train operators of the 975 Omnia bolting machine in underground conditions (Mqworld, 2018). The conference paper by Grajewski et al. (2015) shows that there exists a possibility to utilize a VR headset together with a haptic manipulator for training in of machinery and tool assembly. However, no practical testing is done, and no results are presented.

The three following research papers were found to be the closest to the VUTE thesis, all of them focusing on providing mining-related training with use of virtual reality. Study by Le et al. (2017) describes the development and further testing of a complex tool allowing its user to control a small backhoe excavator using a head mounted display and controllers.

The provided results show that when using the created tool, an operator was fully capable of operating the machinery from a remote location taking on average only 5.67% longer to perform the task of leveling a 1.5 m by 5.5 m area. This study was the first one that clearly has shown that the VR technology can increase the safety within the mining operations by moving the employees away from hazardous areas, while at the same time allowing them to perform their tasks. The second study by Grabowski and Jankowski (2014) evaluates a VR system for rock drilling related training. Conducted with help of 21 participants and utilizing the System Usability Scale, the test compares the usability of the software when displayed using a narrow 45° Field of View (FoV) headset with 110° FoV Development Kit Oculus Rift. Surprisingly the results show that the Oculus Rift display was deemed as less usable than the lower FoV one. However, with scores above 70 both systems were deemed as usable and the researchers concluded that the systems can be applied for training purposes by Kompania Weglowa S.A., Polish hard coal underground mine operator.

The last paper, a report by Hui (2017) contained an extensive overview and classification of available VR input (such as keyboard, mouse, joystick and controllers) and output (VR headsets, 3D screens, projectors) devices, along their advantage and disadvantages. Moreover, the study contains a description of development of a VR software using using Blender 3D modelling software, together with Unity 3D engine. Utilizing the smartphone-based VR headset with gesture recognition camera, the software simulates operating a drilling machine. The described user tests compare users' opinions on operating the virtual machinery with use of the VR system and with a 2D screen together with a keyboard or a joystick. The results show that the participants of the study, have found the virtual reality system more immersive than the 2D screen (4.8 vs 1.3 on a 0 to 5 scale), more intuitive (4.3 vs 2.1), more interactive (3.8 vs 2.6), easier to use (4.0 vs 2.5) and learn (4.4 vs 3.7). The study has also found that some of the users experienced the effect of so called virtual sickness after prolonged use of the VR system.

2.4. Results

The literature review has shown that the number of studies related to the application of the virtual reality technology in mining is extremely small. Only 10 examples of studies and real-life applications of VR were found, out of which 4 were concerned using the technology for training purposes. Out of all, the study by Hui (2017) was the most similar to the following thesis in terms of the structure and the performed tests. The main difference being the fact that the conducted comparison concerned two computer systems – VR and 2D, monitor based one. Moreover, the reported differences were related only to subjective opinions of the users and did not contain any measurements of how well users have performed the given task with use of both systems.

The summary shows that there exists only a very limited amount of studies related to use of VR in mining. Moreover, none of them are related to the subjects of this thesis. Therefore, it is clear that the following thesis is unique and concerns a subject that no one has ever studied before.

3. Development of the VUTE system

Virtual Underground Training Environment (VUTE) is a computer system that provides its users with a possibility to perform geological measurements of rock formations entirely within virtual reality. The system is a combination of two main parts: VR software, and hardware performing the computations and providing the visual stimuli to the user. The idea behind the creation of VUTE was to study the feasibility of using virtual reality systems for training purposes, in this specific case rock wall mapping. The following chapter describes the VR hardware selection process and the development of the VR software.

3.1. Hardware selection

A VR hardware, capable of providing its user with virtual reality, consists of two key elements: headset functioning as a display, and a computer carrying out calculations and logical operations necessary to create a convincing virtual world.

A typical virtual reality headset is comprised of a head-mounted stereoscopic display which provides a separate image to each of the eyes of a person wearing it. Utilizing the principles of binocular stereopsis, the ability to detect depth based on the disparity between viewed images (Howard and Rogers, 1995), the technology displays two slightly offset images tricking the user into perceiving the spatial depth of the rendered object or a scene. Additionally, the VR headsets are capable of tracking movements and angular position of the user's head in the real world and translating them into camera movements within the virtual reality. Together, those two features (the stereoscopic display and the movement tracking) can create an illusion of a virtual world.

A computer capable of running a virtual reality software on modern VR headsets must be able to provide enough computational power to quickly process the data flowing from the headset and in response render two high-quality images that displayed by the headset create an illusion of a 3D environment.

3.1.1. Virtual reality headset

Historically the costs of virtual reality headsets have been very high, ranging from tens to almost a hundred thousand USD. This in return strongly limited the accessibility of the technology for research purposes. Recently, with the new generation of VR headsets, the prices dropped to less than 1000 USD making the technology widely available to consumers (Niehorster et al., 2017).

Currently, available VR headsets can be divided into two main groups: smartphone-based VR headsets and tethered VR headsets. The first group is comprised of devices that utilize smartphones installed by the user within the head-mounted gear as primary displays and sources of computational power. The second group includes standalone devices with built-in displays which are connected to an external computational unit (PC or a gaming console). Table 2 shows the names and parameters of the most popular, commercially available VR headsets that are utilized in modern scientific studies of the applications of the virtual reality.

Table 2. Currently available virtual reality headsets

Type	**Smartphone-based**	**Tethered**		
Name	Varies	PlayStation VR	Oculus Rift	HTC Vive
Platform	Mobile OS (Android or iOS)	PlayStation 4	PC + Mac	PC
Display	Depends on the smartphone installed, up to 3840x2160 pixels at 808 ppi[1]	1920x1080 pixels at 386 PPI[2]	2160x1200 pixels[3] at 386 PPI[4]	2160x1200 pixels[5] at 455.63 PPI[4]
	1920x2160 per eye	960x1080 per eye	1080x1200 per eye	1080x1200 per eye
Field of view	Depends on the smartphone installed	100 degrees[2]	110 degrees[3]	110 degrees[3]
Refresh rate	Depends on the smartphone installed	120 Hz[2]	90 Hz[3]	90 Hz[5]
Position tracking	-	Optical	Optical	Optical
Angular tracking	Inertial	Optical	Optical	Optical
Controller	-	PlayStation gamepad	Oculus Touch	HTC Vive controllers
Price[6]	Depends on the smartphone installed	260 EUR[7]	450 EUR[7]	700 EUR[7]

1 When used with Sony Xperia Z5 Premium (Source: https://www.gsmarena.com/sony_xperia_z5_premium-7536.php)
2 Source: Producer https://www.playstation.com/en-us/explore/playstation-vr/tech-specs/
3 Source: https://www.digitaltrends.com/virtual-reality/oculus-rift-vs-htc-vive/
4 Source: https://xinreality.com/wiki/Pixel_density
5 Source: Producer https://www.vive.com/us/product/vive-virtual-reality-system/
6 Price includes only the cost of the VR headset. Additional external computational unit (PlayStation console in case of PlayStation VR or Mac/PC for Oculus Rift and HTC Vive) is required to use the headset with VR applications
7 Prices as of 10 June 2018 Source: amazon.de

Modern smartphone-based VR headsets lack the necessary hardware to track the user's movement, only hardware angular tracking is possible. In result, software developed for those headsets allows only for controller-induced movement in 3D space. Such type of movement in virtual reality is prone to causing VR (or simulator) sickness in a form of headaches, vision issues, nausea, and disorientation (Kolasinski 1995), an effect which can be strongly reduced when using position tracking instead (Llorach et al., 2014). This, together with the fact that the computational power of today's smartphones is vastly inferior when compared to modern consoles or PCs, resulted in a decision to use a tethered VR headset.

PlayStation VR headset is the cheapest of the modern tethered VR headsets while offering the highest refresh rate. On the other hand, the display is characterized by the lowest resolution and field of view when compared to Oculus Rift and HTC Vive. Moreover, in order to develop software capable of running on PlayStation 4, it is necessary to purchase PlayStation Development Kit which alone is priced around 2500 USD. Having taken those factors into consideration, PlayStation VR was removed from the list of potential VR headsets.

When compared, Oculus Rift and HTC Vive have very similar hardware specifications, with the same headset resolution, the field of view and display refresh rate. Both are capable of precise hardware-enabled position and angular tracking of the user's head and controllers. The main difference between the two would be an 18% higher pixel density of the HTC Vive and its 55% higher price. In the end, the main driver behind the VR headset selection were issues with Oculus Rift reported by teams developing virtual reality software at Aalto University and ready availability of the HTC Vive headset.

3.1.2. PC selection

The hardware requirements for computers running virtual reality software are determined by one main factor – achievable framerate of the displayed virtual scene. The current industry standard of 90 FPS means that in order to provide a comfortable experience a computer has to, in response to signals coming from a VR headset, render a minimum of 90 pairs of high-quality images each second. Low framerates (consistently below 90 FPS) have been proven to often lead to so-called VR sickness, a negative effect similar to motion sickness (Kolasinski, 1995)(Zielinski et al., 2013).

Since the model of the VR headset has a significant influence on the computational power necessary to provide the mentioned 90 FPS minimum, producers publish their own lists of minimum specific hardware requirements. The list for the HTC Vive, headset selected for VUTE, is shown in Table 3.

Table 3. Minimum hardware requirements for HTC Vive

Component	**Model**
CPU	Intel Core i5- 4590 (4 cores, 3.30 GHz) or AMD FX Series 8000 (8 cores, 3.5 GHz) or equivalent
GPU	NVIDIA GeForce GTX 1060 (3 GB GDDR5) or AMD Radeon RX 480 (4GB GDDR5) or equivalent
Memory	4 GB RAM
Video output	1x HDMI 1.4 port, or DisplayPort 1.2
USB	3x USB 3.0 port

Source: Vive, 2018

For the sake of this thesis, the Department of Civil Engineering of the Aalto University was able to provide a PC with hardware components listed in Table 4, which exceeded the minimum requirements. This resulted in a smooth experience for the users and minimized the influence of the low-framerate-induced VR sickness on the obtained results.

Table 4. Hardware specifications of the used PC

Component	**Model**
CPU	Intel Core i7- 4790K (4 cores, 4.0 GHz)
GPU	2x NVIDIA GeForce™ GTX Titan Black (6GB GDDR5)
Memory	32 GB (4x8 GB) Corsair Vengeance RAM
Video output	1x HDMI 1.4 port
USB	3x USB 3.0 port

3.2. Software development

VR software is a type of software designed to generate a virtual 3D environment and, in some cases, to allow for interaction with it and movement within its confines. Created for the thesis, the Virtual Underground Training Software incorporates all of the above-mentioned functions and is comprised of the three main elements:

1. 3D rock wall model – digital 3D scan of an existing section of a rock wall from the Aalto University Underground Research Laboratory, placed in virtual reality;
2. Virtual replicas of geological tools – used for measuring rock wall parameters in VR;
3. User Interface – VR interface utilized by the users to interact with the software.

The following chapter describes the rationales and the steps behind the creation of the three components of the VUTE software.

3.2.1. Generation of the rock wall model

One of the goals stated during the development of the software was to achieve a high degree of realism defined as both the realism of the displayed graphics and models as well as the realism of functions available within the software (Tashiro and Dunlap, 2007). The logic behind it was to allow the users to effortlessly adapt the skills learned in the virtual reality to real-life situations. To satisfy the condition of realistic graphics it was deemed necessary to generate a high-quality 3D model created by scanning a section of a rock wall. Photogrammetry was selected as the most suitable technique, taking into account the high quality of created scans and low entry cost when compared to other techniques, i.e. lidar scanning (Daneshmand et al, 2018)(Snavely, 2008). Moreover, the selected method not only captured the geometry of the scanned object but also its colors, which in return increased the realism of the 3D model and the immersion of the virtual reality scene. From the existing photogrammetry techniques Structure From Motion was ultimately selected. In SFM a set overlapping photo, offset in relation to each other, is processed by a computer software which automatically identifies matching points between pictures (Westoby et al., 2012). Matching points serve as a basis for determining the location and position that the camera/s had in the real world when taking the photographs. In return, this information is used to triangulate the position of the points and recreate the surface of the scanned object (Snavely, 2008).

The rock wall segment selected for scanning is located in the Aalto University Underground Research Lab tunnel, on the southern wall, between the 30^{th} and 40^{th} meter from the entrance. This section was selected for its clearly distinguishable rock joints and lack of shotcrete reinforcement on the surface. The photoshoot took place on the 15th of March 2018 and utilized the setup presented in Figure 1.

Figure 1 Picture of the setup utilized to capture the scene

To enable the camera to capture the fine details of the rock wall, a sufficient amount of light had to be provided to the scene. As the main source of illumination, a set of four floodlights located approximately 3 m from the wall were used, each consisting of two 50W LEDs (eight in total) capable of emitting 4000 lm of light. Light intensity measured with a lux meter on the surface of the rock reached the average value of 409 lux with values in specific parts of the wall shown in Table 5.

Table 5 Measured light intensity in specific parts of the rock surface [lx]

	Left side	**Centre**	**Right side**
Top	380	362	500
Middle	459	470	458
Bottom	336	339	380

Parameters of the used camera and the obtained pictures are presented in Table 6.

Table 6 Parameters of camera and photographs

Parameter	**Value**
Camera	Canon EOS-1D X Mark II
Camera lens	35 mm
Flash	No
Photo resolution	5472x3648 pixels (width x height)
F-stop	f/8
Exposure time	1/500 sec

To achieve a high-quality surface scan, a significant degree of overlap between subsequent photos was necessary, estimated to be equal to a minimum of 60% (Caballero and Dzugala 2018). Shown below is an example of two consequent images taken during the photo shoot with the overlapping area marked in red.

Figure 2 Sequence of two pictures of the rock wall with an overlapping of approximately 65%

In the result of the photoshoot, a total of 232 high-resolution photos were taken. To process the obtained set of pictures into a computer model, in the next stage the obtained images were loaded into VisualSFM ver. 0.5.26 – a computer software developed for reconstruction of 3D models based on the principles of structure-from-motion photogrammetry. Within the program, which was run using the default settings, the pictures were automatically analyzed to detect characteristic points and match pictures containing them. Afterward, the matching points were used by the software as the base when calculating the pose (defined as location plus orientation) that the camera has taken when shooting each picture. In the next steps a sparse 3D point cloud was reconstructed, followed by the creation of a dense cloud of color-coded points making up the scanned surface of the rock wall. The final output of the VisualSFM software was a 3D scan of an area 16.53 m wide and 4.3 m tall, which consisted of 10.9 million individual points, which can be seen in Figure 3. In the last step, the scan was saved into an external file with a PLY format.

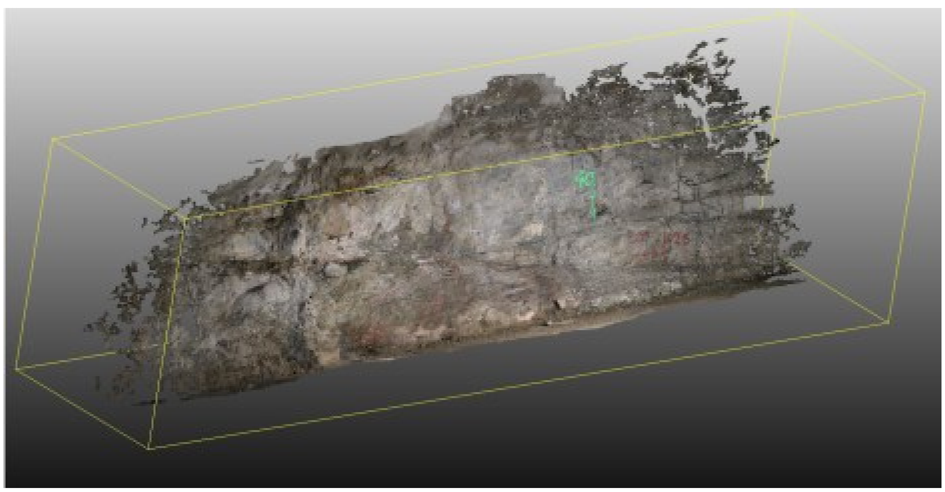


Figure 3 Point cloud generated in VisualSFM. Due to relatively high point density, the surface appears to be continuous even though it is instead made up of individual points

To further process the scanned model, the point cloud was loaded into a 3D processing, open source software CloudCompare ver. 2.9.1. During the first step, the point cloud was cropped to remove the unnecessary, low point density areas on the top and sides of the model. The resulting model was 8.25 m wide (50% of the original) and 3.29 m tall (76% of the original). Measuring the areas of the bounding box the cropped point cloud had the area 62% smaller than the original (27.13 m^2 vs 71.1 m^2) but consisted of only 25% points less (8.16 million vs 10.86 million). The resulting point cloud can be seen below in Figure 4.

Figure 4 View of the point cloud cropped in CloudCompare

In the next step the dense cloud, which consisted of loose points, was transformed into a surface made of the three-dimensional mesh of triangles. For this purpose, a triangulation function "Delaunay 2.5 (best fitting plane)" available in CloudCompare was used with its default settings. The rock surface model that was created in the result, consisted of the original number of 8.16 million points now creating 16 million triangles. Such model resolution, defined as the total number of triangles creating a surface of the model, was too high to render and display in VR at the desired frame rate of 90 FPS and higher. In perspective, the current AAA games include in a single scene models with a number of triangles not exceeding 2 million (Polycount, 2018), a value eight times lower. Therefore, a significant simplification of the model was necessary. To achieve a balance between the software performance (expressed through framerate) and the quality of the model, the mesh was split into two parts: inner, high-quality mesh used for taking measurements and outer, low-resolution model used to increase the immersion.

To simplify the meshes, the models had to be loaded into external software, namely MeshLab v2016.12. However, the large file size of the scans, resulting from their high resolution, had the potential to significantly impact the performance of MeshLab and extend the time necessary to process the files. Therefore, it was necessary to select a file format that would result in a low file size.

The CloudCompare output file formats included: *PLY (binary encoding), PLY (ASCII encoding), OBJ, STL (binary encoding), STL (ASCII encoding), OFF, BIN, VTK, FBX (binary encoding), FBX (ASCII encoding), FBX (encrypted), FBX 6.0 (binary encoding), FBX 6.0 (ASCII encoding), FBX 6.0 (encrypted), DXF* and *MA*. Figure 5 shows file sizes resulting from different file formats, obtained for an example model consisting of 1 071 964 vertices and 2 213 287 polygons.

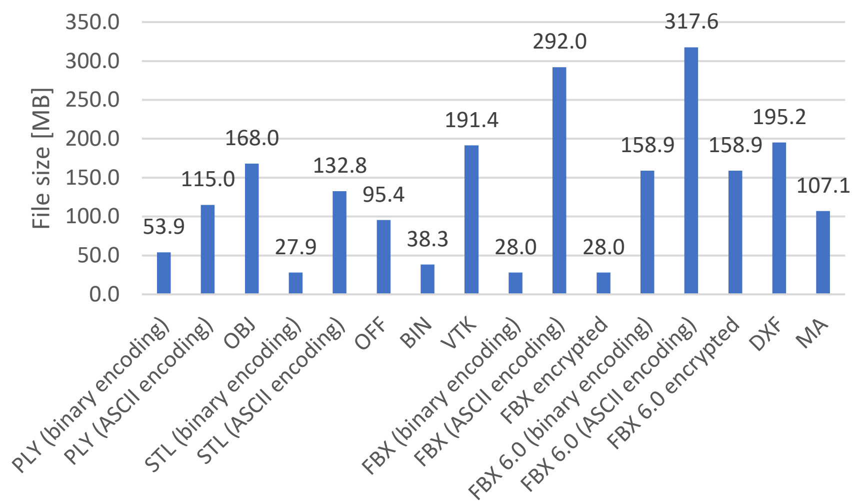


Figure 5 CloudCompare output file sizes corresponding to different file formats

STL (binary encoding), STL (ASCII encoding) and *OFF* file formats were immediately excluded from further assessment because the only information saved was related to the geometry of the mesh, while the vertex colors storing information about the colors of the scan, were not supported. Furthermore, *BIN, VTK, FBX* (all types), *DXF* and *MA* file formats were omitted since they were not accepted by MeshLab. Ultimately, the *PLY (binary encoding)* file format was selected as the one with the smallest file size. The resulting 53% to 68% file size reduction, when compared with also feasible PLY (ASCII encoding) and OBJ formats, lead to a significantly more efficient use of hard drive space and shorter loading times of the files, an important factor when operating on 3D scans, which have the potential to reach the size of hundreds of GBs for high quality meshes.

Once loaded into the MeshLab, both the inner and outer meshes were simplified using the Quadric Edge Collapse Decimation function. The input parameters used for simplification of the models and rationale behind the selected values are presented in Table 7.

Table 7 Quadric Edge Collapse Decimation parameters

Parameter	Value	Comment
The target number of faces	2 million (for the inner model) 100 thousand (for outer)	The parameter describing the number of triangles left because of simplification. Specific values were selected based on the industry standards[1]
Percentage reduction	- (0-1)	Not utilized, used the above option instead
Quality threshold	1 (0-1)	Value determining how close to the original triangle shapes will the faces of a simplified model be[2]
Preserve boundary of the mesh	No	The parameter determining if the outer edge of the mesh will be unaffected by simplification[2]. Using the option resulted in a high mesh distortion; therefore, in this case, it was left unchecked
Preserve Normal	Yes	Determines if remeshing will change the normals of the model triangles[2]. Set to yes to preserve the original values
The optimal position of simplified vertices	Yes	Determines whether a position of the new vertex is calculated based on the position of the two original ones when collapsing an edge of a mesh. When turned off the new vertex is placed in the location of one of the two original ones[2]. Set to yes to achieve a higher quality model
Planar simplification	No	Determines whether an additional constraint is added when simplifying the mesh[2]. Set to no, since it is only useful in the case of models with large, planar areas[2]
Weighted simplification	No	Applies different levels of simplification to the selected sections of the model. Set to no to achieve uniform simplification of the whole surface
Post-simplification cleaning	Yes	Removes artifacts and loose points resulting from the process. Set to yes to receive initially cleaned up model
Simplify only selected faces	No	Allows the user to select which faces will be simplified. Set to no, since the whole model was set to be simplified

[1] Source: Polycount, 2018
[2] Source: Shapeways, 2018

Because of simplification, the resolution of the inner part of the rock wall scan decreased by 57% from six to two million triangles. In the case of the outer mesh, the decrease was significantly larger, equal to a 99.1% drop in the number of triangles. The exact values of the parameters of both models are presented in Table 8 and Table 9. The significant difference in quality between the two meshes can be clearly seen in Figure 6 which shows both overlapping.

Table 8 Parameters of the inner model

Parameter	**Original value**	**Value after simplification**	**Change**
Width [m]	3.550	3.550	-
Height [m]	1.105	1.105	-
Depth [m]	2.015	2.015	-
Projected area [m^2]	7.154	7.154	-
Number of vertices	2,326,676	999,920	-57.02%
Number of triangles	4,630,354	1,999,920	-56.81%
Total area of triangles [m^2]	20.36	19.13	-6.08%
Point density [points/mm^2]	0.11	0.05	-54.24%

Table 9 Parameters of the outer model

Parameter	Original value	Value after simplification	Change
Width [m]	4.255	4.255	-
Height [m]	1.021	1.021	-
Depth [m]	1.695	1.695	-
Projected area [m^2]	19.978	19.978	-
Number of vertices	5,829,912	50,112	-94.87%
Number of triangles	11,598,877	99,712	-99.14%
Total area of triangles [m^2]	45.90	31.87	-30.56%
Point density [points/mm^2]	0.13	0.0016	-98.76%

Figure 6 Re-meshed high-quality inner model and low-quality outer model with a border marked in red

To perform a final clean-up of the created models, the files were exported to Blender ver. 2.79 – an open source 3D modeling software. To ensure good performance and short loading times, an appropriate MeshLab output file format had to be selected. MeshLab supported the following file formats: *3DS, PLY (binary encoding), PLY (ASCII encoding), STL (binary encoding), OBJ, OFF, WRL, DXF, DAE, CTM,* and *XYZ.* Shown in Figure 7 are the corresponding file sizes for an example model made of 1 071 964 vertices and 2 213 287 polygons.

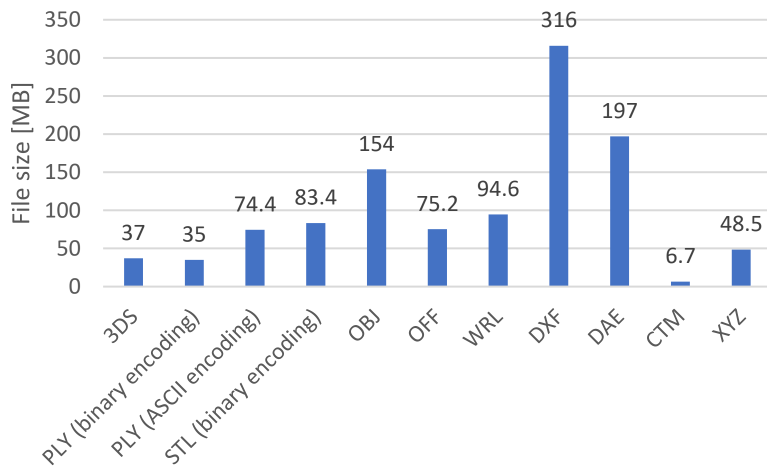


Figure 7 MeshLab output formats and corresponding file sizes

Based on those values, the smallest file size was achieved with *CTM* format. However, *CTM* was not supported by the Blender software, and in result, the *PLY (binary encoding)* file format was selected, as the one with the second smallest size. The resulting reduction of the hard drive space usage between 5% and 88.9% has again proven that the *PLY (binary encoding)* file format has a significant advantage over the others and is the most suitable when creating 3D scans for the use in virtual reality.

Using Blender software, the model was prepared for use inside the 3D engine. Loose vertices of the model were removed, surface normals were flipped to ensure proper model rendering, and the scan was rotated by 180°. Afterward, the model was ready to be utilized in the virtual reality software.

3.2.2. 3D engine selection

To speed up the process of developing the virtual reality software, a decision to use a readily available 3D engine was made. A typical 3D engine consists of several ready tools that are meant to accelerate the process of creating video games and applications, such as scene editor, content manager, physics, texture and sound editors. In 2018 the two most popular PC 3D engines were Unity 3D with a 48% market share, followed by Unreal Engine with 13% (Patel, 2018). Both engines include similar functionality and support the most popular virtual reality headsets. Ultimately, the Unity 3D engine was selected because the Aalto University had a ready available Unity Education license as a participant in the Unity License Grant Program. The development of the VR software was done entirely using the Unity 3D editor ver. 2017.2.19748287.

3.2.3. VR software development

The overall realism of a scene is a sum of two main factors: the realism of graphics and realism of functions. While lifelike graphics increase the immersion of a scene, realistic functions in a virtual learning environment increase its educational value by allowing the users to apply in real-life skills that they have learned and practiced in VR. Moreover, in the case of VUTE by accurately reproducing the way that measurements are taken made the comparison of the VR and real-life results possible. Following this logic, a set of rock parameters that would be measurable in the software were selected, namely: a dip angle of a rock joint set, dip direction, joint spacing, and joint roughness coefficient. Listed parameters are basic values measurable in in-situ conditions that are widely utilized in mining to describe spatial relations and geometry of rock joint surfaces. Those values, together with groundwater conditions, shape and size of blocks are critical when designing excavations in underground mines (Hoek et al., 1995) and in the result, the ability to correctly and efficiently measure them is crucial for a mining engineer.

One of the first things that were considered when designing the software was the input system. An example of an input system used with a normal 2D computer software can be a keyboard and a mouse. However, in VR, where user's gestures must be registered in three dimensions, alternative methods must be used. There exist several readily available input devices available for modern virtual reality systems, ranging from controllers included in headset bundles to third-party systems capable of tracking user's hand movement and detecting gestures.

Initially both systems were considered for VUTE; however, ultimately the controllers provided with HTC Vive headset were selected. The decision was driven by several factors: their superior tracking precision, accurately detectable button presses and by issues with hand tracking systems reported by other teams developing virtual reality projects at Aalto University (Krupakar, 2017).

To allow users to measure the parameters of the rock wall in a way that would correspond to the real life, the VUTE software was set to include a set of virtual replicas of tools normally used to measure the dip angle and dip direction of a joint set, joint spacing, and the joint roughness coefficient.

The dip angle of a rock joint can be defined as an expressed in degrees angle of deviation of its surface (or planar simplification of the surface) from the horizontal plane. Dip direction is measured as an azimuth between a line representing the dip of a surface, projected on a horizontal plane and the north direction. Visual representation of those two parameters is shown in Figure 8.

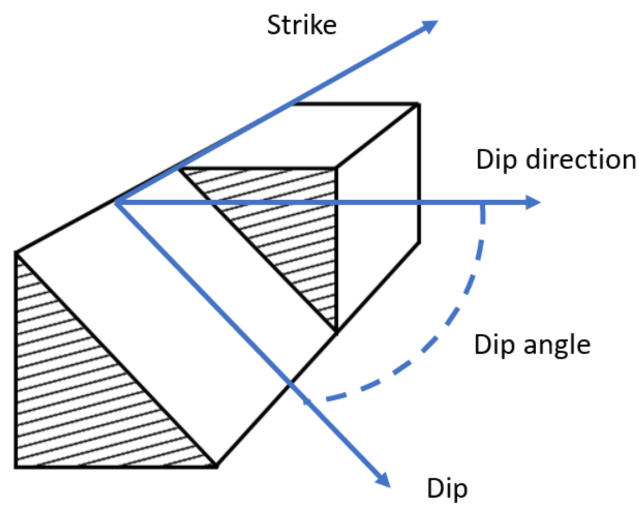


Figure 8 Visual interpretation of a dip and dip direction of a surface

In real life, one of the basic devices used for measuring values of both dip angle and dip direction are geological compasses. Even though their design may range from magnetic to fully electronic, the principle remains the same with one part of the compass designed to measure the azimuth of a surface's dip and the second to assess its inclination. Figure 9 shows an example of a geological compass that was used as a base for designing the VR version of the tool.

Figure 9 Picture of a commonly used type of a geological compass (Source: Aliexpress.com)

To make the system more transparent and user-friendly, the virtual reality version of the geological compass was designed to consist of two entirely separate tools: VR compass for measuring dip direction of a surface and VR protractor for assessing its dip angle. Shown in Figure 10, the VR compass was attached to the user's controller and precisely followed his or her hand movements. The tool included three main parts: a lower body with a numerical dip direction scale, compass ball with a red line pointing to the northern direction and a semi-transparent top display. To measure a dip direction user had to position the front, outward facing side of the compass against a surface and press the trigger button on the controller. After the trigger button was pressed the top display would show the value of a measured dip direction. In case of a surface dipping towards the user, one must manually adjust the reading by adding 180º. This limitation can be later resolved by implementing a feature automatically detecting the direction in which a surface is inclined. Like in real life, to get the most accurate reading, the VR compass had to be held with its lower body in a horizontal position, which was indicated by the compass ball switching colors from black to green. Such compass design including a large automatic display is different from the design of a classic geological compass but was dictated directly by the relatively low resolution of the selected VR headset. The pixel density of the built-in display was simply not high enough to enable easy and accurate readings from the analog scale on the compass and thus such compromise had to be implemented.

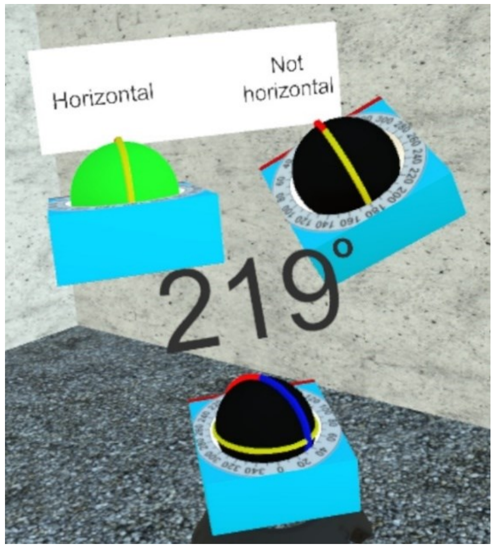


Figure 10 VR compass in the front showing a dip direction of 219°. On the second plane, two dummy compasses are presented, with the left one indicating horizontal position of the compass with a green color of the compass ball

For measuring the dip angle of a rock joint surface in VR a protractor tool was created. Its overall design and the working principle behind it was designed to be very similar to that of the VR compass as it can be seen in Figure 11. The three main parts of the protractor were again the body with a scale, a ball fixed in a horizontal position and a large display. To avoid the users confusing the two tools, the body of the protractor was colored green instead of light blue like in the case of the compass. To get the dip angle reading a person was supposed to put either the left or the right side of the protractor (marked in red) against a surface and press the trigger button after which the value would be displayed above the body of the compass.

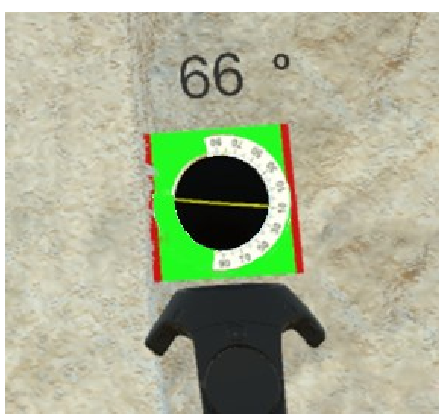


Figure 11 HTC Vive controller with a VR protractor above it displaying the dip angle of 66°

Joint spacing refers to either the apparent joint spacing or normal joint spacing. Apparent joint spacing is measured during a scanline survey of joints and can be defined as a distance between two neighboring joints (belonging to the same set) measured at their intersection with a scan line. On the other hand, the normal or true joint spacing is the distance between two joints measured along a line perpendicular to both joints (Wong, 2015). In this thesis, the term joint spacing will refer to the latter one. In real life situation, a joint spacing is usually measured using simple tools like rulers or measuring tapes. In the VR an equally simple approach was selected. The VR version of a ruler was made up of a six-sided box, one meter long with a centimeter scale on four of its sides as it is shown in Figure 12. A similar design like in the case of a VR compass or protractor, including an automatic measurement and value display, was not incorporated in the VR ruler. The reason behind it is explained later in this chapter. In the case of the VR ruler users had to "manually" measure the distances by placing the ruler in the desired spot and reading the values from the analog scale on the tool.

Figure 12 VR ruler used to measure joint spacing on a rock wall scan

Joint roughness coefficient (JRC) is used to describe the geometrical conditions of a surface of a rock joint. Together with joint wall compressive strength (JSC) can be used to calculate a shear strength of a joint surface, a value crucial when assessing the stability of designed mine openings (Barton, 1973). Joint roughness coefficient is defined as a numerical value from 0 to 20 obtained by comparing the profile of an actual rock surface with a standardized profile chart (Hoek et al., 1995). Reading of a linear profile of a rock surface is usually done with the use of Barton's comb which can be seen in Figure 13. In the case of VUTE, the profile chart selected was the industry standard chart developed by Barton and Choubey was utilized, which is presented in Appendix 6.

Figure 13 Plastic Barton's comb showing a profile of a rock surface

In order to measure the JRC inside the virtual reality, a VR version of Barton’s comb was developed, consisting of two main parts: the model of an actual black and red Barton’s comb attached to one controller and the JRC chart attached to the other controller as seen in Figure 14.

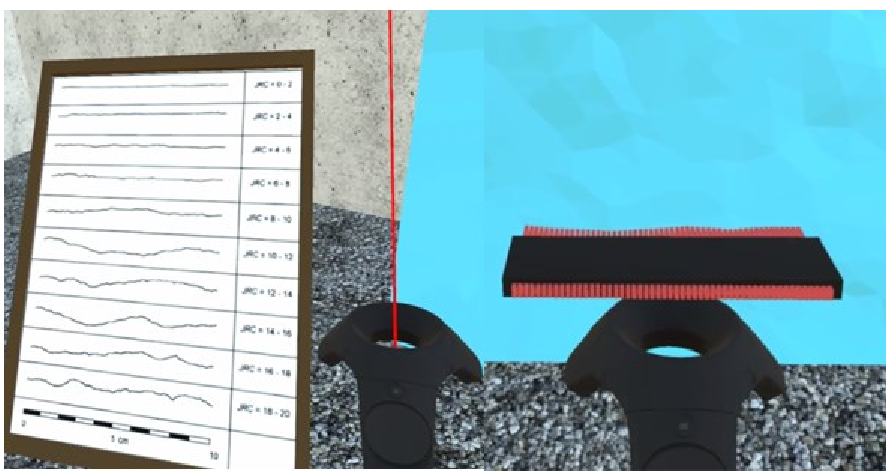


Figure 14 HTC Vive controllers and the tool used for measuring the JRC in VR consisting of Barton's comb (on the right) and the JRC chart (on the left)

Similarly, as in the case of the VR ruler, the tool lacked the automatic measurement feature. The reason behind it was dual: first, the value of JRC is obtained by comparing the profile with a ready chart and is thus highly subjective, a characteristic that the author aimed to include in the VR; second of all the automatic reading would require a substantially more advanced approach including detection of a collision between the measuring tool and a measured object. Modern 3D engines are not designed to detect collision between multi-faceted, high-resolution models consisting of hundreds of thousands of triangles. Instead, the collision calculations are performed for simple, invisible 3D shapes (called *colliders*) which are overlaid on high-resolution models resulting in an illusion of detecting the interaction between the complicated objects. Such an approach, successfully used in video games, was not applicable in this situation as explained below. The high-resolution model used in the VR software was made up of 2 million triangles, a number that vastly exceeded the capabilities of the Unity 3D engine which at the time limited collision detection to colliders made of up to 255 triangles, a value that was over 7.8 thousand times too small (Unity, 2018).

The first element of the user interface created for the VUTE software was the tool wheel – a circular menu designed as a method of switching between the created VR tools. By clicking the large touchpad button located on the top of the right controller users could circle through available measurement devices. To ensure that the menu would be intuitive and easy to read, four contrasting colors were used together with simple icons representing each of the tools. The tool wheel is depicted in Figure 15.

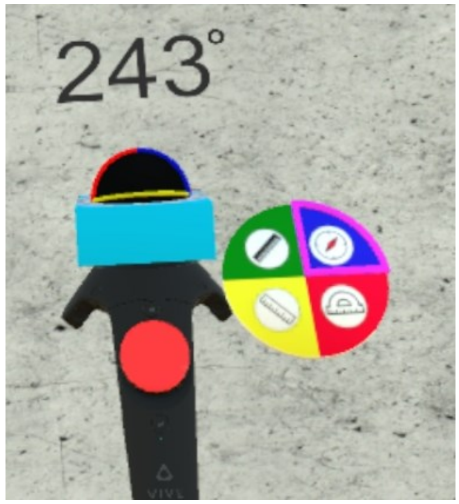


Figure 15 Tool wheel (right side of the picture) with a red circle marking the touchpad of the HTC Vive controller, used to circle through the menu

As a way of interacting with menus and inputting measurement values a very popular design of a "VR laser pointer" cursor was implemented in the system, which consisted of a "laser" ray emanating from the top of the left controller. By aiming the beam on a part of the user interface and clicking the trigger button user could interact with various elements of the scene. Figure 16 depicts an example of an interaction of a user with a button using a laser pointer

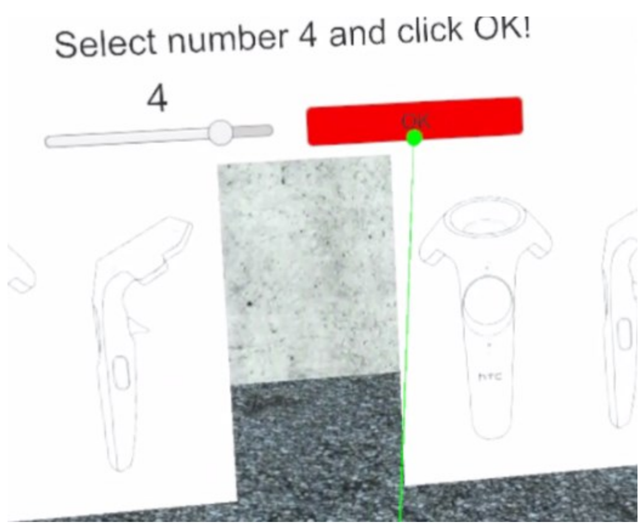


Figure 16 User interacting with the interface of the system with a laser pointer tool

With technology advancements, VR equipment is becoming cheaper and more accessible to the general public than ever before. Therefore, to ensure that the previous experience with VR, or lack of thereof, would have a minimal impact on user’s performance, it was decided that each virtual visit to the tunnel would be preceded by a tutorial covering all the aspects of the system. To eliminate the human factor from the equation and to provide a consistent, identical teaching to each of the users, a VR tutorial was implemented in the system. As shown in Figure 17, the tutorial consisted of a series of instructions written on boards and presented to the user. The covered topics included in this order: basics such as looking around in VR, interacting with the User Interface using the laser pointer as well as operating the VR tools and taking the measurements.

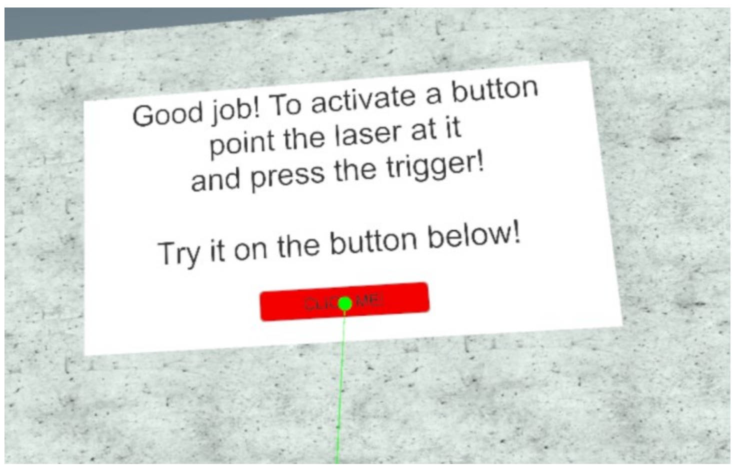


Figure 17 An example of a tutorial board containing instructions on how to interact with buttons inside VR

After a user had gained the necessary skills to operate within the virtual reality, he or she would be moved from the room containing the tutorial to the second stage of the virtual tunnel visit. The second, final location contained two distinctive objects: the 3D scan of the rock wall and the answer sheet. By design, the user would conduct the measurement of the rock mass parameters on the model using the provided VR tools and input the obtained values on the answer sheet using the laser pointer. The values would later be stored and evaluated. Figure 18 shows the high-resolution scan with a surrounding lower resolution version as well as the instructions for the exercise.

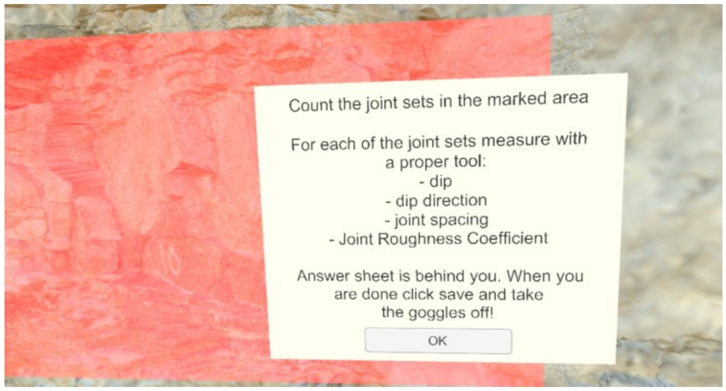


Figure 18 High-resolution scan of the tunnel wall marked in red, surrounding low-quality model and the board with the description of the task

As shown in Figure 19, the answer sheet consisted of a simple white board and a table of sliders used to input the numerical values for each of the measured parameters.

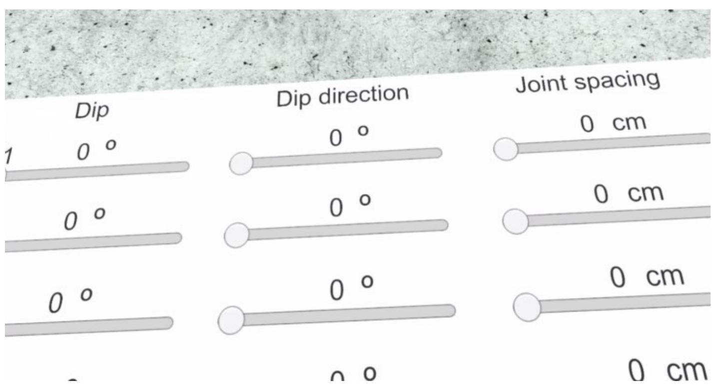


Figure 19 Answer sheet used in the first version of the VUTE software

In VUTE the movement of the user within the virtual reality, a matter often causing issues for many VR programs, was limited to only replicating the real-life motion of the user, thus limiting the effective VR space to the confines of the real-life room that the experiment was taking place in, namely a 2x2m square.

The VUTE software was developed in Unity 3D engine by the author with 3D models created and edited in Blender 3D modeling software. However, to enable the use of HTC Vive VR headset within the engine the following external libraries were utilized: SteamVR Plugin ver. 1.2.3, and Virtual Reality Toolkit (VRTK) ver. 3.2.0.

To correctly display the colors of the 3D scan, a custom shader was created since natively Unity 3D engine does not include an option to display vertex colors and thus initially rendered the 3D scan as white (default color).

By default, scripting in the Unity engine is done using the JavaScript, C# and/or Boo programming languages. Since the author at the time did not possess the skills necessary to efficiently write scripts in Unity and to save on time necessary to develop those, an external visual scripting addon was used. Playmaker ver. 1.8.6 enabled development of scripts through diagrams made from premade blocks and was utilized to program all the function within the VUTE software.

4. VUTE feasibility study

The VUTE feasibility study was conducted in order to gather data on four elements related to learning with the use of the virtual reality software:

1. The effectiveness of learning through VR;
2. The efficiency of learning through VR;
3. The realism of the VUTE system;
4. The usability and the learnability of the VUTE system.

The effectiveness of learning stated was characterized as the capability of users to provide the correct answers. In the study, the effectiveness was determined as the number of correct measurements of the rock wall parameters made by the participants. Proving that the VR system had similar or better learning effectiveness than the real-life tunnel visit would allow drawing a conclusion that it is applicable for learning purposes.

By the efficiency of learning, the author identified the time that the participating students were required to spend in order to perform one full set of measurements of the rock wall parameter measuring exercise, in both situations.

The realism can be defined as the fidelity with which user perceives the virtual reality when compared to the real life (Bowman and McMahan, 2007). It is an important part of the VUTE software for two reasons: first is that modern studies suggest that the high realism and resulting immersion of simulations has a positive influence on the learning outcomes, by allowing users to transfer the skills acquired in virtual reality to real-life situations (Dede, 2009)(Tashiro and Dunlap, 2007). Second is that by making the virtual visit similar to the real one would allow for the direct comparison of the learning outcomes of the two situations. As a way of measuring the realism of the VUTE system, the author decided to identify and evaluate the differences between real life and virtual tunnel visits.

Lastly, the usability of the VR system is defined as the degree to which users can utilize a system to reach set goals in a way that is effective and efficient (ISO 9241, 2018). On the other hand, learnability can be interpreted as the degree of difficulty with which a user is able to learn how to use a system (ISO/IEC 25010, 2011). Both aspects of the system can be identified as interconnected, with learnability being sometimes defined as one of the attributes describing usability rather than a standalone parameter (Sanchez et al., 2009). If by measuring the two values, the system would be proven to be highly unusable and hard to learn, it would be certain that those two factors had a strong influence on the results: measurements themselves, the time necessary to perform them etc. Therefore, by showing that the system was properly designed, would allow drawing a conclusion that the results were not distorted by it.

The following chapter describes the setup and the outcomes of the two experiments conducted by the author to answer the research questions and to verify the hypothesis.

4.1. VUTE First experiment

The two main goals of the first experiment were to provide data that would allow answering the research questions and testing the hypothesis, as well as to generate the feedback which would later be used to identify and correct flaws in the VUTE software before the second experiment.

4.1.1. Expected results

To determine the effectiveness of learning, the author collected the measurements of rock wall parameters obtained in both situations: VR and real life. To assess their correctness, the values were to be compared with baseline values obtained by the experienced members of the Aalto University staff during the second experiment. Furthermore, the subjective views of the users on the quality of learning through both approaches were collected in a form of written answers to questions about personal opinions on the learning outcomes.

To evaluate and compare the efficiency of learning through both approaches, the duration of the following tasks in VR and in the tunnel were measured: activities not directly related to learning (travelling to the place of measurements, gearing up, safety briefing etc.), passive learning (getting familiar with the instructions related to the exercise) and active learning (performing measurements and inputting answers).

The author aimed to measure how realistic and similar a VR tunnel visit is to a real-life experience through finding and measuring the differences between those two. This has been done in two ways: direct and indirect. Direct way included measuring the distance perception of the users in VR and real life. The reason behind it was that identifying and measuring spatial relations between objects was a crucial part of the exercise, and potential differences in depth perception might have had an influence on the obtained values. As the indirect way of identifying variances between the two experiences, the author collected and analyzed written answers to open questions, given by the participants.

To assess the usability and learnability of the VUTE system, the System Usability Scale was used. Developed in 1986 by John Brooke, the SUS is the industry standard and has been utilized in numerous studies focused on the usability of various computer systems. To assess the SUS score, the user has to express his opinion on each of the ten statements about the system in a form of a number between one and five, where one is “strongly agree” and five is “strongly disagree”.

The statements cover multiple characteristics of the usability of a system, including its complexity, ease of use, need for support while using it etc.

Furthermore, through several open questions, author gathered user feedback about the developed VR software from the participants of the experiment, to further improve the Virtual Underground Training Environment and enhance the learning experience for its future users.

4.1.2. First experiment timeline and methods

The first VUTE experiment took place over seven days, between 13th and 23rd of March 2018 and was conducted according to the layout presented in Figure 20.

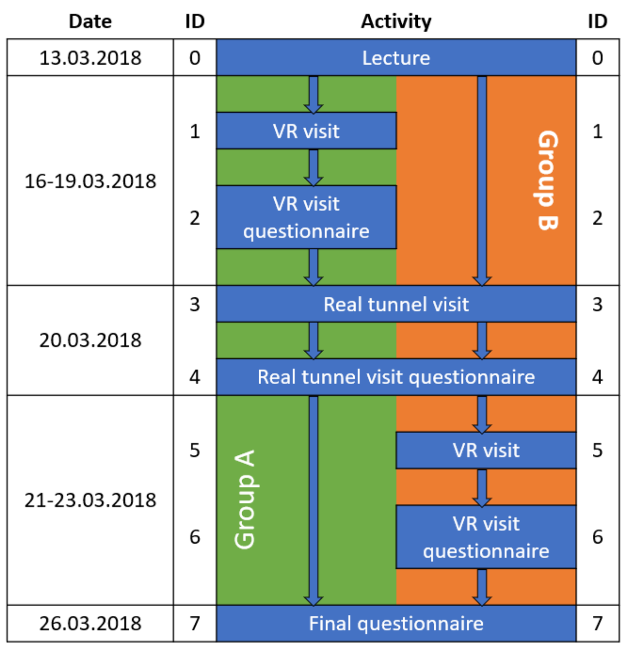


Figure 20 Timeline of the experiment

Involved in the experiment were 20 students from the Engineering Geology course taught at the Department of Civil Engineering of the Aalto University. Table 10 shows the exact number of students participating in each of the activities on a given day.

Table 10 Timetable of the experiment

Date	Activity	Number of participants
16 March 2018, Friday	VR tunnel visit, group A	4
19 March 2018, Monday	VR tunnel visit, group A	6
20 March 2018, Tuesday	Tunnel visit, both groups	20
21 March 2018, Wednesday	VR tunnel visit, group B	4
22 March 2018, Thursday	VR tunnel visit, group B	1
23 March 2018, Friday	VR tunnel visit, group B	5

4.1.3. Lecture (ID: 0)

Initially, on Tuesday the13th of March, the participants attended the lecture about the rock wall mapping, given as a part of the curriculum of the Engineering Geology course. The presented material included the theory of rock wall mapping and its methods, followed by an in-class hands-on practical introduction to using the geological compass and Barton's comb. After the lecture, the participants were split into two groups of ten, with each group set to follow a different order of the experiment. This approach was selected specifically to investigate whether the learning order, that is VR visit followed by a real tunnel visit or vice versa, had any influence on the educational outcome. Moreover, the supervisors ensured that the number of people with previous experience in rock wall mapping was comparable in each of the groups to minimize its influence on the overall performance of each of the groups

4.1.4. VR experience (IDs: 1 and 5)

Beginning with the Group A, the students were asked to participate individually in the VR version of the tunnel visit, during which they were tasked with performing rock wall mapping measurements according to the instructions shown in Figure 21.

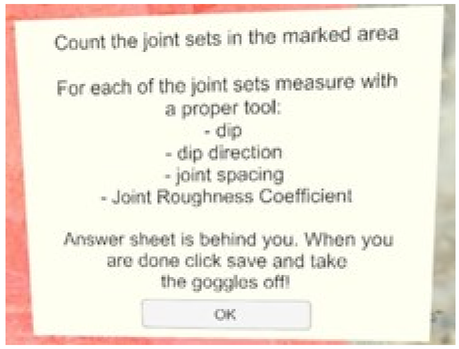


Figure 21 Instruction for the participants, presented in the VR with an area of interest marked in red

For the whole high-resolution section of the scan, the task was to estimate the amount of the rock joint sets. Furthermore, for each of the identified joints, the participants were asked to measure the parameters listed in Table 11.

Table 11 Parameters estimated during the VR tunnel visit

Parameter	Way of measuring	Type of the measurement
Dip	VR geological compass	Objective
Dip direction	VR protractor	Objective
Joint Roughness Coefficient JRC	VR Barton´s comb/observation	Subjective
Joint spacing	VR ruler	Objective

To gather data later used to assess and quantify the differences in distance perception inside the VR, the participants were asked to estimate and note the length of the perpendicular three lines, each laying along of the three axes. Figure 22 presents the three lines, each marked with a distinctive color and the answer sheet used to input the answers.

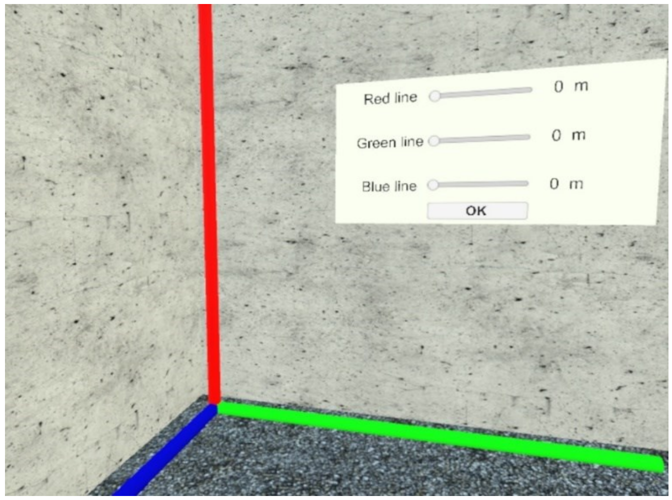


Figure 22 Three lines and the answer sheet

During the whole VR tunnel visit, using a stopwatch the supervisor was measuring: the set-up time spent on gearing up (labelled as the time not directly related to learning), time spent in the VR tutorial and the exercise introduction (labelled as the passive learning time) and the time actually spent on taking the measurements (labelled as active the learning time).

4.1.5. VR visit questionnaire (IDs: 2 and 6)

Immediately after the VR visit to the tunnel, each of the participating students was asked to fill out a questionnaire about his or her experience (presented in Appendix 1). The questionnaire consisted of five main parts:

1. Questions about the previous VR experience;
2. Questions about his/her view on the learning outcomes of the VR tunnel visit;
3. System Usability Scale questionnaire;
4. Feedback on the VR visit and the created system;
5. Questions asking about the design insights (What can be improved and why?) should be added to the questionnaire

4.1.6. Tunnel visit (ID: 3)

On the 20th of March 2018 the whole group consisting of 20 students, under the guidance of two employees of the Department of Civil Engineering of the Aalto University visited the Underground Research Tunnel. During the practical exercises, participants were tasked with measuring the same rock mass parameters as in the VR (namely dip and dip direction of rock joints, Joint Roughness Coefficient, and joint spacing), on the same section of the tunnel, using real-life versions of the geological tools. Moreover, during the visit students assessed lengths of three metal rods, which had the exact same length and orientation as their virtual counterparts. Furthermore, during the visit the author (not counted towards the supervisors) measured the duration of the following:

1. Set-up time - the time necessary for: traveling from the tunnel entrance to the location of the exercise, gearing up, safety briefing, gear removal and travelling back to the tunnel entrance;
2. Passive learning time – time spent on the theoretical introduction to the exercise;
3. Active learning time – time actually spent on performing the exercise.

4.1.7. Tunnel visit questionnaire (ID: 4)

Immediately after the measurements, while still in the tunnel, the participants were asked to fill out the questionnaire about their subjective experiences during the exercise (presented in Appendix 2). The questionnaire consisted of about their experience during the exercise. The questionnaire will consist of three main parts:

1. Question about the previous rock wall mapping experience of the participants;
2. Questions about their subjective view on the learning outcomes of the exercises;
3. Feedback on the quality of the experience and proposed changes.

4.1.8. Final questionnaire (ID: 7)

All 20 students were asked to fill out the final questionnaire once all the members of the two groups have participated in both the VR experience and the actual tunnel visit. The questionnaire was focused on pointing out the differences between the VR and the real underground environments and consisted of two parts:

1. Questions about students' opinion about the differences in the quality of learning tunnel mapping in virtual reality and during the actual tunnel visit;
2. Open questions about the differences between the VR environment and the actual tunnel.

4.1.9. Results

The total number of participants of the first VUTE experiment was n=20, out of which six were female and 14 were male. The youngest student was 22 years old during the experiment, while the oldest was 30. The mean age was 25 years old and the median was 24. Figure 23 shows the histogram of the age of all 20 participants of the experiment.

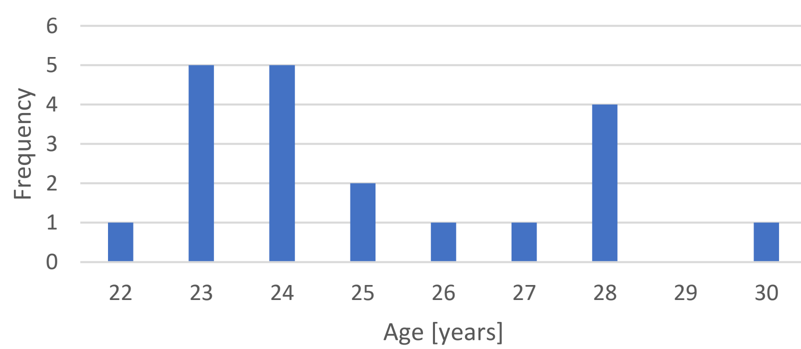


Figure 23 Distribution of the age of participants

Prior to the VUTE experiment, 70% of the students have never done any tunnel mapping. 25% have done it "once or twice" and only one had experience that extended beyond that. Shown in Figure 24 is the overview of the answers.

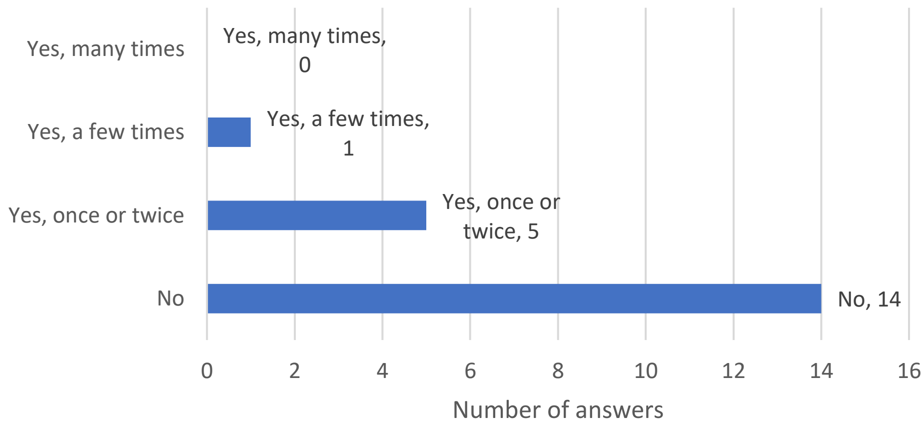


Figure 24 Distribution of answers about previous tunnel mapping experience

Asked about the familiarity with virtual reality systems, the majority of participants (12 out of 20 or 60%) stated that they had no previous experience with VR at all, with only eight users having used VR “once or twice” or “a few times”. Figure 25 presents the detailed distribution of the answers.

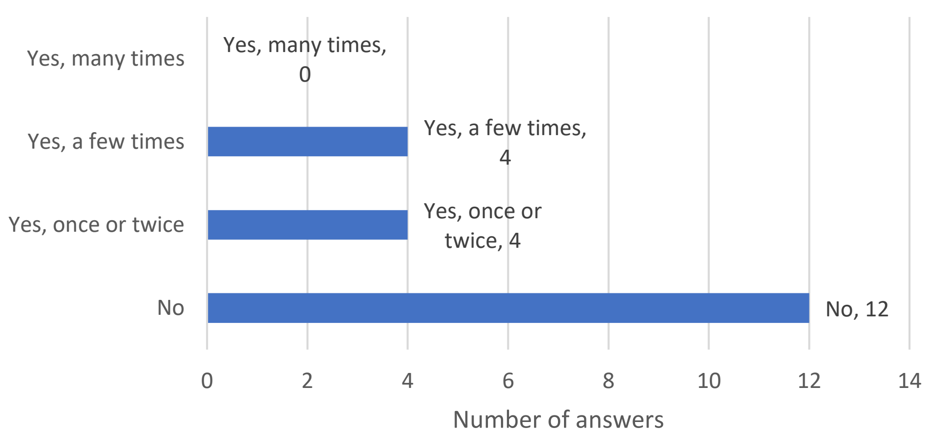


Figure 25 Histogram of answers to a question about prior experience with VR technology

Playing First Person Shooter games have been proven to enhance person’s spatial cognition (Spence and Feng, 2010), a trait which can be defined as an ability to acquire, process and use spatial information.

Taking this effect into account, the author decided to measure if the participants of VUTE were active users of FPS games and use the information to later assess whether this might have influenced the outcomes of the study. As pictured in Figure 26, most of the students stated that they “never or almost never” play First Person Shooter games, with three people playing them once a month and four once a week.

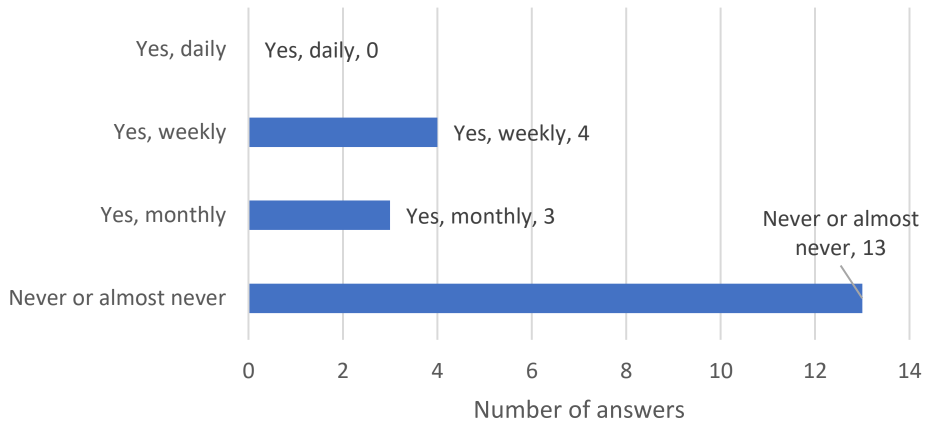


Figure 26 FPS gaming habits among the participants

Nausea resulting from the simulation sickness is a commonly reported issue, that had the potential of influencing the outcomes of the experiment by making the users rush through the VR exercise. As shown in Figure 27, when asked in the final questionnaire about their experience 55% of the participants stated that they did not experience any nausea at all.

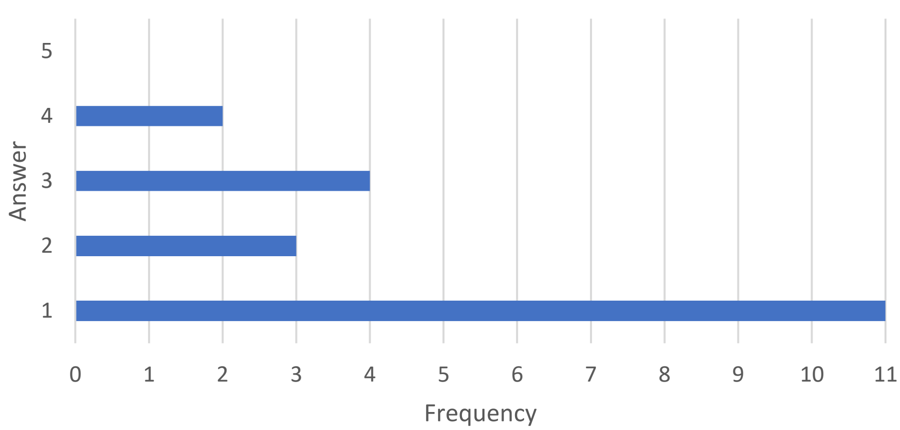


Figure 27 Answers given to the question about how they agree with the following statement: "I experienced nausea during the VR experience" where 1 - totally disagree and 5 - totally agree

The T1 set-up time for the VR tunnel visit was defined in the study as the amount of time it took a user to walk into the room, gear up, adjust the headset, start the VUTE software and after the exercise remove the headset and leave the room. Measured by the author, acting as a passive observer, the T1 ranged from 0.40 to 6.67 minutes (an outlying value, resulting from issues with headset display sharpness that occurred for a person wearing prescription glasses) and resulted with an average value of 1.45 minutes.

For the real tunnel visit, the T1 included the time necessary to walk through the underground tunnel from the entrance to the changing room, gear up, reach the section of the tunnel where the exercise took place and later walk back to the changing room, remove the gear and walk back to the entrance/exit. The T1 was equal to 18.62 minutes and only one measurement has been made because all the participants were traveling together as a group.

When compared, the VUTE system allowed its participants to save on average 17.17 minutes as shown in Figure 28. The over 92.2% decrease in the duration of the activities not directly related to learning was the first documented advantage of using the VR software.

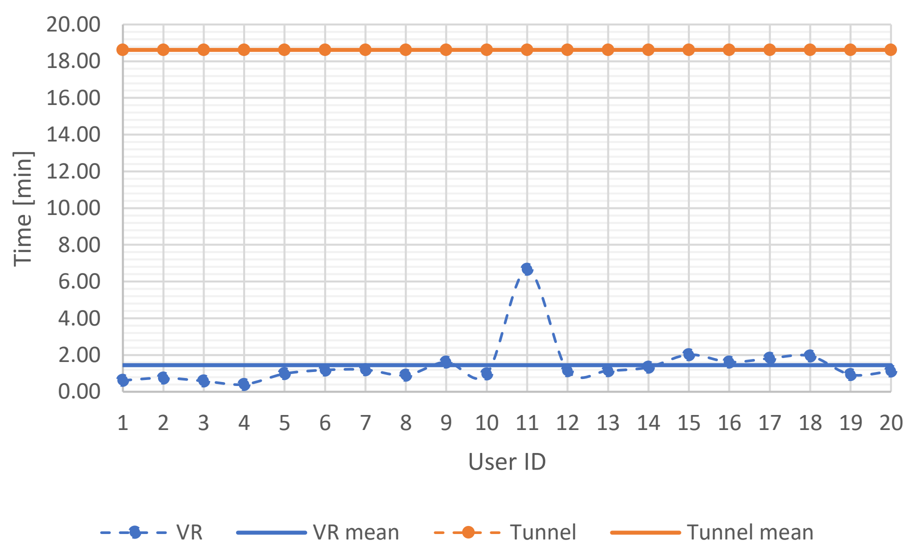


Figure 28 T1 values during the VR and real-life tunnel visits

The T2 passive learning time in virtual reality included the time required to complete the tutorial and read the instructions for the exercise. The VUTE participants spent between 3.18 and 11.42 minutes on this task, achieving an average of 6.10 minutes. When compared with the T2 for the real-life tunnel visit, which reached the values from 1.53 to 5.33 minutes and an average of 2.48 minutes, the VR took 3.62 minutes longer. Most likely, the main driver behind the VR passive learning taking on average 145.6% longer than the tunnel visit was the necessity to include the tutorial in the VR software. However, in this matter, there exists a large room for future optimization. Figure 29 shows the T2 values that each of the 20 users achieved.

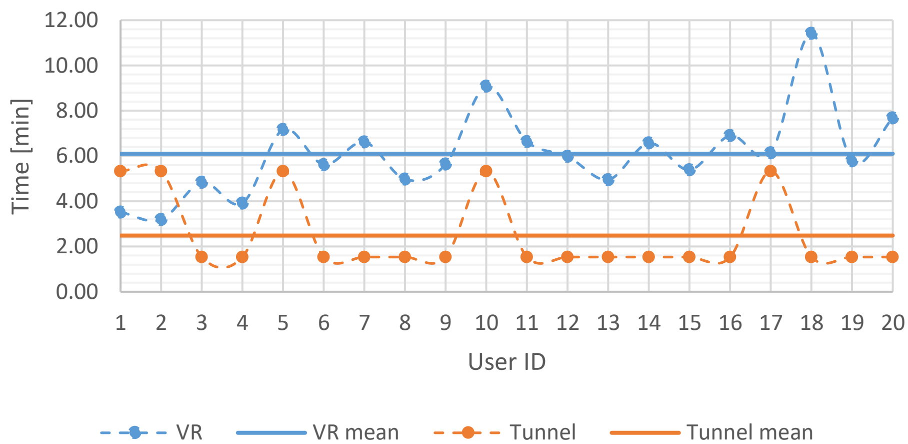


Figure 29 T2 for VR and visit to the real tunnel

The active learning time (T3), in both the VR and real-life case, was the time that the participants devoted only to taking the measurements. For the VR visit the values ranged from 4.65 to 20.23 minutes, and for the real-life visit between 17.65 to 21.78 minutes. On average, the virtual reality measurements took 6.25 minutes less (12.43 vs 18.68 minutes). The results can be seen in Figure 30.

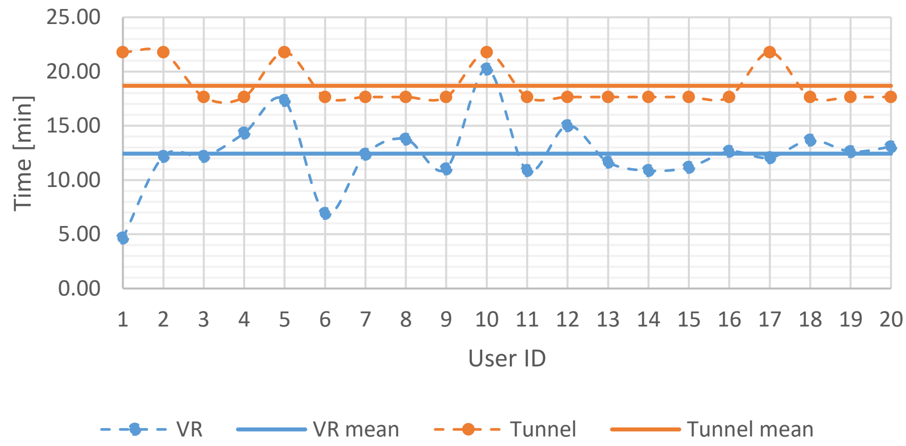


Figure 30 Active learning times achieved by the participants

The total average duration of the VR exercise (T1+T2+T3) was 19.98 minutes, 49.8% shorter than the average 39.78-minute-long tunnel visit. The time saving resulting from the use of the VUTE software ranged from 10.75 to 36.95 minutes, with an average value of 19.81 minutes. The detailed results of the time measurements are presented in Table 21 in Appendix 4.

The measurements of the time required to perform the exercise (T2+T3) were tested for statistical significance using the average difference paired t-test. For this purpose, two hypotheses were stated:

$H_0: \mu_0 = 0$ Stating that based on the sample data, the difference between reported times is not significant;

$H_1: \mu_0 \neq 0$ Stating that based on the sample data, the difference for the whole population is significant.

First, the T2+T3 values reported for VR were subtracted from their real-life counterparts resulting in a set of 20 values. Later the mean value of the dataset was calculated ($\bar{d} = 2.64\ min$) along with its standard deviation $\sigma = 5.46\ min$. The standard error was calculated using the Equation 1:

$$s_e = \frac{\sigma}{\sqrt{n}} = \frac{5.46}{\sqrt{20}} = 1.221 \tag{1}$$

Where:

n – the number of positions within the dataset, -.

Afterward the test statistic (t-value) was calculated according to the Equation 2:

$$t = \frac{\bar{d}}{s_e} = \frac{2.638}{1.221} = 2.161 \tag{2}$$

With the use of Microsoft Office Excel, the probability value (p-value) was estimated for two-tailed Student's t-distribution using DIST.2T function using the t-value and the number of degrees of freedom $n - 1 = 20 - 1 = 19$. The resulting p-value of 0.044 was smaller than the assumed significance level of α=0.05 and thus the null-hypothesis was rejected in favor of hypothesis H1. The experiment has provided enough evidence to state that reported time differences are statistically significant, or in other words ,the reported time gain did not occur due to luck.

To test whether the time it took the users to perform the exercise (T2+T3) was influenced by their previous experience with the VR technology, the Pearson's sample correlation coefficient was calculated using the Equation 3:

$$r_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = -\frac{0.775}{4.451 * 0.821} = -0.212 \tag{3}$$

Where:

cov(X,Y) – covariance between X (reported VR experience) and Y (time required to finish the exercise), -;

σ_X, σ_Y – standard deviation of X or Y, s.

The resulting value of $r = -0.212$ implies a weak negative linear correlation between the two values for the data obtained during the experiment. This shows that in the sample data, the resulting time was to a small degree influenced by the prior VR experience. Figure 31 shows the plotted relationship between the two values.

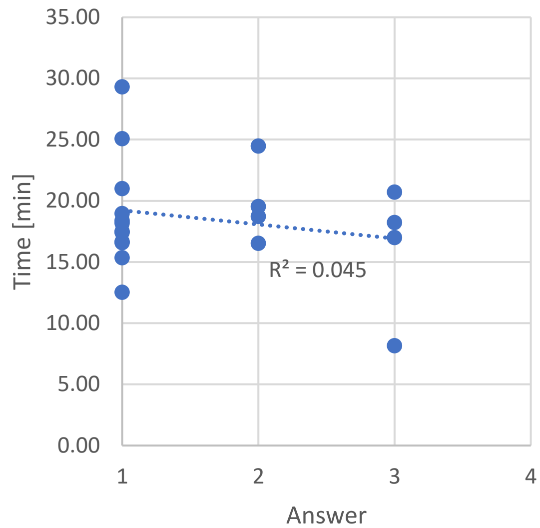


Figure 31 Correlation between VR experience and the total time required to finish the task. Numbers on the vertical axis represent 1 – No previous VR experience, 2 – Having used VR once or twice, 3 – Having used VR a few times, 4 – Having used VR many times.

As mentioned above, the linear relationship was assessed using only a sample of the total population. Therefore, it was necessary to verify whether the reported dependency was strong enough to be relatable to the whole population. This was done using the significance of the correlation coefficient test. Firstly, two hypotheses were stated:

$H_0: \rho = 0$ Stating that based on the sample data, the population correlation coefficient is not significantly different from zero;

$H_1: \rho \neq 0$ Stating that the population correlation coefficient is significantly different from zero.

To test the null hypothesis H0, the t-value for the dataset was calculated using the Equation 4:

$$t = r_{X,Y} * \sqrt{\frac{n-2}{1-r_{X,Y}^2}} = -0.212 * \sqrt{\frac{20-2}{1-0.045}} = -0.921 \tag{4}$$

Where:

n – the amount of time measurements (n=20), -.

The resulting t-value, along with the number of degrees of freedom ($n - 1 = 20 - 1 = 19$) was later used to estimate the p-value (probability value) for two-tailed Student's t-distribution using the Microsoft Office Excel function T.DIST.2T.

The outcomes of the calculations were as follows: $t = -0.921$ and $p = 0369$. When compared, the p-value was larger than the assumed significance level $\alpha = 0.05$ and the null hypothesis H0 was not rejected. The experiment did not provide enough evidence to show that the correlation coefficient is significantly different from zero and that there is a significant linear relationship between the reported VR experience and the time necessary to complete the exercise.

The correlation between the reported gaming habits and the duration of the exercise (T2+T3) was also verified. The sample coefficient of correlation between the gaming habits and the duration of the exercise (T2+T3) $r_{X,Y} = -0.421$ showed a moderate negative correlation between the two values proving that within the sample, the gaming habits of the participants might have allowed them to perform the task quicker. Figure 32 depicts the plotted relationship. However, testing the correlation for statistical significance showed that the experiment did not provide enough data to prove it meaningful for the assumed level of significance, with probability value $p = 0.064$ exceeding the $\alpha = 0.05$. The dataset used for the test and the values of the calculated coefficients are shown in Appendix 4, Table 22.

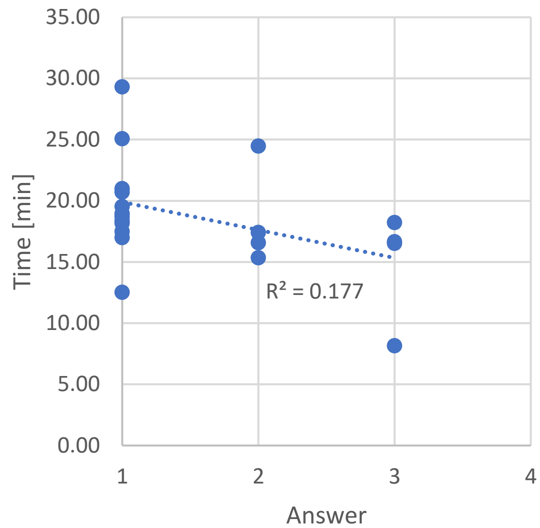


Figure 32 Relation between FPS gaming habits and total time necessary to complete the VR exercise (T2+T3). Numbers on the vertical axis represent 1 – Playing FPS games never or almost never, 2 – Playing FPS games monthly, 3 – Playing FPS games weekly, 4 – Playing FPS games daily.

In the case of the relationship between tunnel mapping experience and time required to perform the task, the reported linear relationship within the sample was very weak negative. The $r_{X,Y} = -0.098$ shows that within the group, the experience in taking rock wall measurements had vera y small influence on the duration of the exercise, as depicted in Figure 33. The performed statistical test has shown that there is insufficient data to prove that the reported relationship in significantly different from zero. The numbers used for the statistical test are presented in Appendix 4, Table 22.

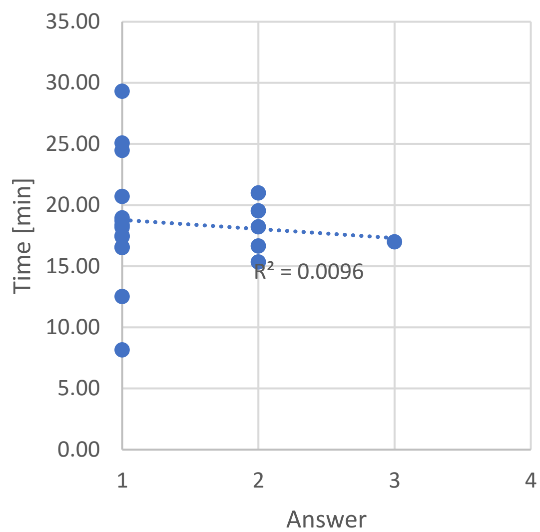


Figure 33 Correlation between previous rock wall mapping experience and achieved the T2+T3 time. Values on the vertical axis represent 1 – No prior tunnel mapping experience, 2 – Having measured rock wall parameters once or twice, 3 - Having measured rock wall parameters a few times, 4 - Having measured rock wall parameters many times.

The assessed relationship between reported nausea and the total time spent on the VR exercise (T2+T3) can be seen in Figure 34. The calculated Pearson's coefficient of linear correlation ($r_{X,Y} = 0.101$) shows a very weak, positive correlation between the two values. This allows drawing a conclusion that within the sample the time necessary to perform the exercise was not influenced by the experienced nausea to a meaningful degree. However, when tested ($t = 0.430$ and resulting $p = 0.672 > \propto = 0.05$) it was proven that the there is insufficient evidence to show the statistical significance of the linear relationship. The exact values used for the test are presented in Table 13 in Appendix 5.

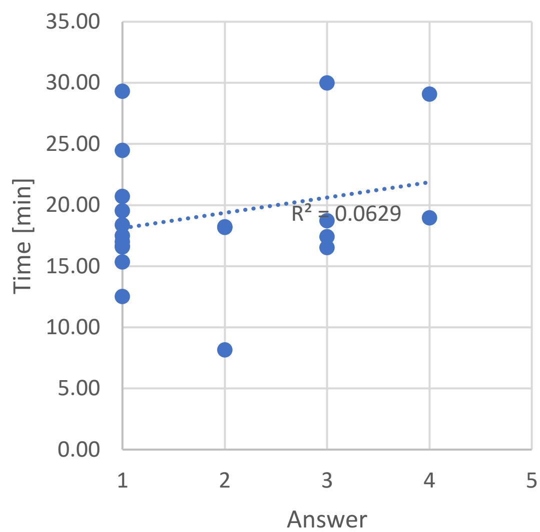


Figure 34 Relation between reported nausea and the total time spent in VR (T2+T3). The values on the horizontal axis represent how the responders agreed with the statement "I experienced nausea during the VR experience" with 1 meaning “totally disagree” and 5 – “totally agree”

The usability of the VUTE VR system was assessed using the industry standard – the System Usability Scale, a tool designed in 1986 by John Brooke to measure the usability of computer systems. To assess the usability score of the VUTE system, its users were asked to answer 10 questions with values from 1 (totally disagree) to 5 (totally agree). The full questionnaire is presented in Appendix 1. Later, the numerical answers given for questions 1, 3, 5, 7 and 9 were added together and 5 was subtracted from their total sum. For questions 2, 4, 6, 8 and 10 the sum was subtracted from 25. In the end, both values were added together and multiplied by 2.5 to obtain the numerical usability score.

Calculated based on the answers given by the 20 participants, the usability scores ranged between 55.0 and 90.0 with a mean value of 72.25. Figure 35 shows the distribution of SUS scores reported by the users of VUTE.

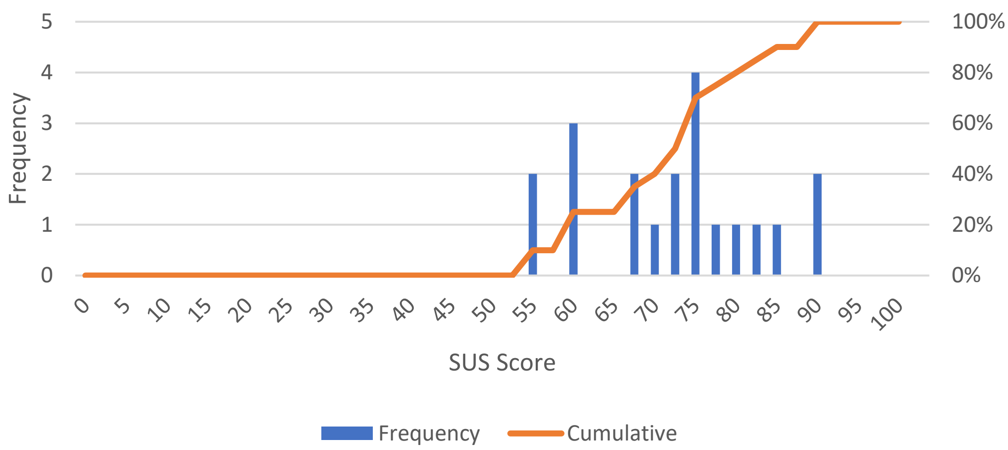


Figure 35 Distribution of SUS scores

According to the paper published by Bangor et al., (2009) on how to interpret the SUS scores, the average value of 72.25 results in VUTE system achieving the adjective rating of “Good” and implies that the system’s usability is acceptable and, according to its users, the system is designed in a way that makes it fit for the purpose of measuring the rock wall parameters.

According to Lewis and Sauro (2007), it is possible to assess an additional factor using the System Usability Scale – the learnability. Learnability is defined as the level of ease with which a person is capable of learning how to use a system. To assess its score the numerical answers to questions 4 and 10 from the SUS questionnaire must be summed up and multiplied by 12.5.

The resulting average value of 72.50 indicates that the VUTE system was perceived by its users as having a good level of learnability. The distribution of the learnability score is shown in Figure 36.

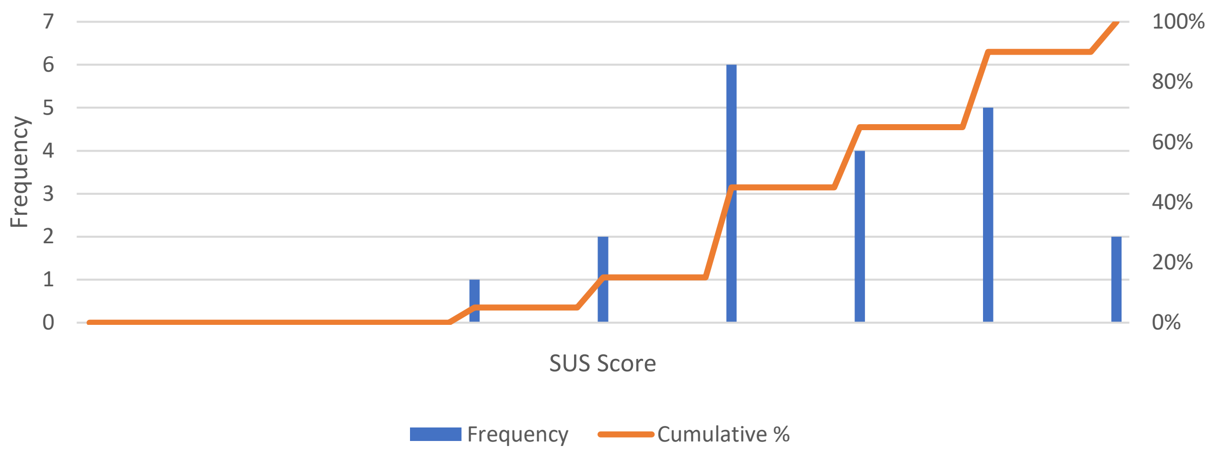


Figure 36 Distribution of learnability score among the users of the VUTE system

Comparing the reported usability of the system with the total time required to complete the VUTE VR exercise (T2+T3), as presented in Figure 37, shows a weak, negative correlation ($r_{X,Y} = -0.348$). This shows that to a small degree the users who considered the system as more usable, might have been able to finish the exercise faster. However, when tested ($t = -2.026$ and $p = 0.057$) the correlation is proven to be statistically insignificant. The dataset used for the test can be seen in Appendix 4, Table 25.

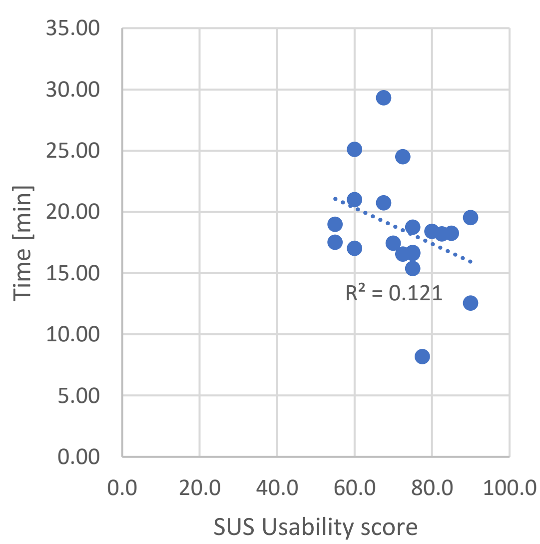


Figure 37 Relationship between reported usability of the system and the total time (T2+T3) required to complete the exercise

The same thing was proven when comparing the reported learnability of the system and the time it took each user to perform the task (T2+T3). The estimated weak negative correlation ($r_{X,Y} = -0.379$) was proven to be statistically insignificant ($t = -1.740$ and $p = 0.098$). Figure 38 shows the plotted relationship between the two values. The whole dataset can be seen in Appendix 4, Table 25.

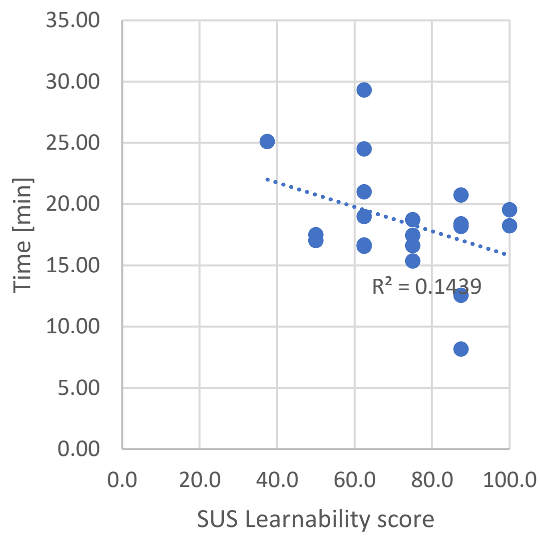


Figure 38 Relationship between the learnability of the system and the time required by each user to finish the exercise

4.1.10. Conclusions and path forward

According to the results of the first VUTE experiment, when compared to the real-life tunnel visit, performing the exercise in VR allows for saving on average 20 minutes. 17 minutes were saved during the set-up alone and further 2 minutes during the measurements part of the experiment. The drop in the duration of the exercise itself was proven to be statistically significant and not to have occurred randomly. However, for the results to be meaningful it was necessary to show that in terms of the learning outcomes, the VUTE software was as at least as good or better than the real-life tunnel visit. To do that, the author decided to compare the number of correctly measured rock wall parameter. Therefore, a set of correct, baseline values was necessary to be used when to identify the right answers. For this purpose, the second experiment was designed, this time including the Aalto staff experienced in taking the rock wall measurements.

Described and tested were several dependencies between the time required to finish the exercise and various factors. However, when determining the degree of correlations, it was proven that the measured time T2+T3 was not in a meaningful way distorted by neither of the factors. However, when tested for statistical significance, none of those correlations was confirmed to be statistically significant.

Studied using the SUS, both the usability and learnability of the VUTE system were proven to be above average for computer systems and free of significant issues. Therefore, the system was proven to be fit for its purpose. In the sample, weak correlations were found between the reported usability, learnability and time spent on taking the measurement, but none of them has been proven to be statistically significant.

To further improve the VUTE software the author, according to the PDCA cycle (Plan, Do, Check, Act) utilized by Aalto University in quality management, evaluated the feedback generated by users during the first VUTE experiment. After analyzing a list of 26 most common issues, four of them were selected to be resolved before the second VUTE experiment. The full list can be seen in Table 12 below.

Table 12 List of the issues with the VUTE system reported by the user during the first VUTE experiment. Resolved issues are in bold

Issue	Explanation	The frequency of being mentioned	Why it has been selected/omitted	How was resolved
Imprecise answer inputting	**Inputting the answers required precise movement of the VR controller, which was problematic for some users**	**Mentioned by 45.0% of participants (9/20)**	**Most common issue; Decreased value input precision and the usability of the system**	**Additional [-5] [-10] and [+5] [+10] buttons were added to the answer sheet allowing for easier answer input**
Barton's comb did not work automatically	The Barton's comb was not giving an automatic reading when the controller button was pressed, unlike the VR compass	Mentioned by 25.0% of participants (5/20)	At the time of the experiment, the available technology did not allow for detection of a collision with very detailed models like the 3D wall scan used in VR	-
Not enough instructions for wall mapping	The VR lacked instructions on how to measure the rock wall parameters	Mentioned by 25.0% of participants (5/20)	Implementing instructions would alter the experiment outcomes and make them incomparable with previous ones	-
VR area was too small	**The VR area in which the measurements took place was too confined and caused discomfort in users**	**Mentioned by 20.0% of participants (4/20)**	**Discomfort caused by the issue had the potential to negatively influence the ability of the user to learn and properly perform exercises**	**The area within VR was extended by moving the wall further away from the user**
VR headset resolution was low	The low resolution of the headset caused the wall scan to appear blurry and unrealistic	Mentioned by 20.0% of participants (4/20)	The schedule of the experiment did not allow for waiting for additional hardware purchase, delivery, and setup	The issue was not resolved before the second experiment due to lack of time. In future stages purchasing higher resolution headsets is recommended
Lack of haptic feedback	The system did not provide haptic feedback when putting VR tools against the surface of the scan	Mentioned by 10.0% of participants (2/20)	As mentioned before, the technology at the time did not allow for detecting collision with high-resolution models	-

<table>
<tr><td>VR caused dizziness/nausea</td><td>VR caused nausea/dizziness in some of the users</td><td>Mentioned by 10.0% of participants (2/20)</td><td>A serious issue that could influence every aspect of the VR experience and render the whole system unusable</td><td>Before each experiment users were instructed on how to act in case of nausea</td></tr>
<tr><td>The tutorial area did not correspond to actual dimensions of the room</td><td>The issue caused one of the participants to collide with a wall while in VR tutorial</td><td>Mentioned by 5.0% of participants (1/20)</td><td>Even though the issue was mentioned only by one person it was serious enough (potential harm and injury) that it was resolved</td><td>Outline of the real floor was added in the tutorial section of VR</td></tr>
<tr><td>Blurry vision</td><td rowspan="18"></td><td rowspan="18">Each mentioned by 5.0% of participants (1/20)</td><td rowspan="18">Issues were not relevant enough (mentioned by too few people) to be resolved</td><td rowspan="18"></td></tr>
<tr><td>Bleak wall model colors</td></tr>
<tr><td>Ruler did not work automatically</td></tr>
<tr><td>Real life area was too small</td></tr>
<tr><td>VR tools were hard to operate</td></tr>
<tr><td>No option to go back in the tutorial</td></tr>
<tr><td>Distorted space in VR</td></tr>
<tr><td>Being watched while taking measurements</td></tr>
<tr><td>Measuring felt "stupid"</td></tr>
<tr><td>VR headset cable</td></tr>
<tr><td>Taking measurements wasn’t efficient</td></tr>
<tr><td>VR equipment was uncomfortable</td></tr>
<tr><td>VR is impractical for measuring large areas</td></tr>
<tr><td>Lack of cooperation</td></tr>
<tr><td>Distinguishing joint sets</td></tr>
<tr><td>Measuring joint spacing</td></tr>
<tr><td>The software was "laggy"</td></tr>
<tr><td>Lack of immersion</td></tr>
</table>

4.2. VUTE Second experiment

4.2.1. The aim of the experiment

The main goal of the second experiment was to provide the baseline rock wall parameters' values to use when assessing the correctness of answers given by the participants of the first experiment. Furthermore, to benefit the future VR training and learning software, the author aimed to verify whether the implemented changes to the software resolved the reported issues, whether the usability and learnability have improved and to collect further feedback on the system.

4.2.2. Experiment timeline and methods

The experiment took place over 14 days and was split into two stages. During the first one, which took place between 26th of April and 16th of May, the 11 members of the Aalto staff have been introduced to the improved VR software and tasked with measuring the exact same rock wall parameters as in the feasibility test, that is the dip, dip direction, Joint Roughness Coefficient JRC and joint spacing. Afterward, participants were asked to fill out a questionnaire about their experience. The questionnaire, presented in Appendix 5, was a simplified version of the VR questionnaire used during the first experiment and consisted of three parts:

1) Questions about the previous VR and rock wall mapping experience;

2) System Usability Scale;

3) Feedback on the VR visit and the UI of the system

On the 17th of Mary, during the second stage of the experiment, seven of the employees (four had to drop out due to scheduling issues) performed the rock wall measurements in the real underground tunnel. The results of the second experiment are presented in the following chapter.

4.2.3. Results of the second experiment

Total of 39 sets of measurements, including all four selected rock wall parameters, were taken within the Virtual Reality by 11 participants and three joint sets were identified. The outcome of the measurements of dip and dip direction can be seen in a form of a stereoplot in Figure 39, which was created using Stereonet 10.0 software developed by Richard W. Allmendinger. Marked in yellow are measurements that were incorrect – did not belong to any of the distinguished joint sets.

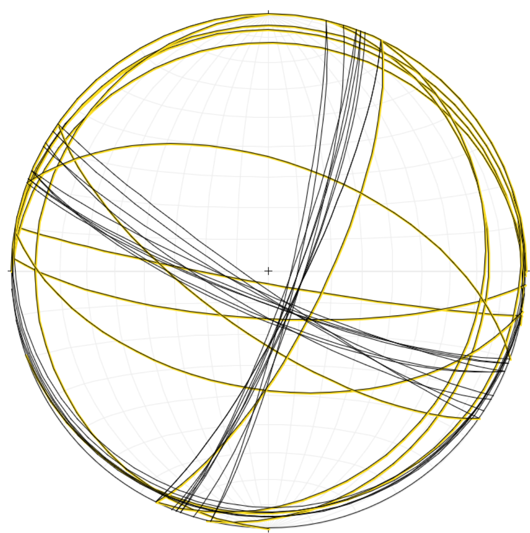


Figure 39 Stereoplot of dip and dip direction values measured by Aalto employees in Virtual Reality. The values that did not belong to any of the three joint sets (incorrect values) are marked in yellow.

The measurements (after excluding the incorrect ones) were then used to calculate the mean value of each parameter for all three joint sets individually. The parameters of the obtained measurement datasets, along with the averages can be seen in Table 13.

Table 13 Parameters of datasets containing measurements made in VR for all identified joint sets

	JS1				**JS2**				**JS3**			
	Dip	DipDir	JS	JRC	Dip	DipDir	JS	JRC	Dip	DipDir	JS	JRC
Mean	80°	110°	21	6	80°	205°	18	8	5°	180°	9	6
Min	76°	103°	11	2	75°	200°	7	4	2°	169°	8	3
Max	83°	116°	28	12	85°	215°	28	10	8°	190°	10	12
St. dev	2.02°	4.30°	7.43	2.88	3.12°	5.06°	5.52	2.06	2.06°	8.18°	0.98	3.37

During the real-life tunnel visit, a total of 22 measurements were taken by 7 members of the staff and the procedure described above was repeated. The stereoplot showcasing measured the dip an dip direction values is shown in Figure 40. The parameters of the collected datasets representing each of the three joint sets are presented in Table 14.

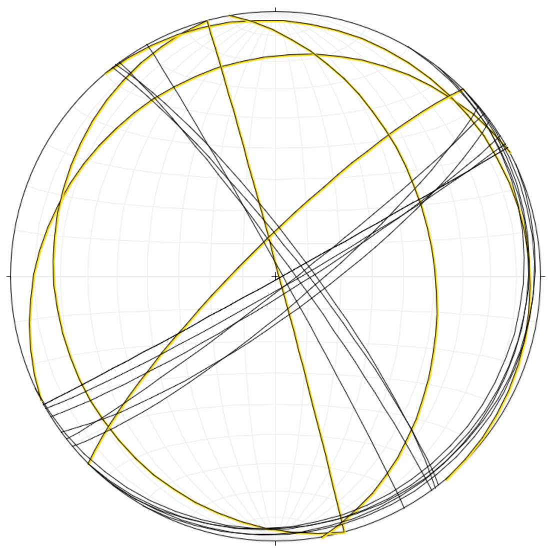


Figure 40 Stereoploted values measured by Aalto staff in the actual tunnel. Incorrect measurements (not belonging to any joint set) are marked in yellow

Table 14 Parameters of datasets describing three joint sets

	JS1				**JS2**				**JS3**			
	Dip	DipDir	JS	JRC	Dip	DipDir	JS	JRC	Dip	DipDir	JS	JRC
Mean	84	55	22	5	85	147	21	6	6	135	8	5
Min	80	52	12	2	78	140	8	3	4	120	5	3
Max	88	61	35	6	89	151	55	10	9	155	10	8
St. dev	3.03	3.54	8.70	1.50	3.92	4.20	14.62	2.43	1.62	11.60	2.23	1.72

The previous mapping experience of the participants of the second VUTE experiment was assessed using a questionnaire (see Appendix 5). Possible answers to the question “Have you ever done tunnel mapping before?” included: 1 – No; 2 – Yes, once or twice; 3 – Yes, a few times; 4 – Yes, many times. The most often given answer was “3 – Yes, a few times”. The calculated average value was 3.09 and the median was 3.0.

The usability and learnability of the system were assessed using the same methodology as during the first VUTE experiment. Based on 11 sets of answers to the SUS questionnaire, the mean usability of the improved VUTE system was reported to be 82.27 which resulted in an adjective score of “Good”. In terms of learnability, the new score was 84.09 showing a “Good” level of learnability.

The written feedback on the second version of the VUTE software was grouped and is presented below in Table 15.

Table 15 Grouped feedback on the second iteration of the VUTE software

Proposed change	**Amount of mentions**
Higher resolution	3 (mentioned by 27.3% of users)
Automatic measurements	2 (mentioned by 18.2% of users)
Barton's comb including collision detection	2 (mentioned by 18.2% of users)
Ability to draw on the model	2 (mentioned by 18.2% of users)
More freedom to move, including the ability to move vertically	2 (mentioned by 18.2% of users)
Materials with exercise theory available in VR	2 (mentioned by 18.2% of users)
Adding audio recordings to the system	1 (mentioned by 9.1% of users)
Automatic input of measurements	1 (mentioned by 9.1% of users)
Ability to cooperate within VR	1 (mentioned by 9.1% of users)
Ability to move the ruler in relation to the controller	1 (mentioned by 9.1% of users)
Ability to input answers with both controllers	1 (mentioned by 9.1% of users)
Spreadsheet capabilities in VR	1 (mentioned by 9.1% of users)
Generation of stereoplots in VR	1 (mentioned by 9.1% of users)
Instant feedback on measurements	1 (mentioned by 9.1% of users)

4.2.4. Conclusions and path forward

The second experiment has successfully fulfilled its main purpose of providing the baseline values for assessing the correctness of the measurements made by students. However, when comparing the measurement made in VR with those taken in real-life it can be clearly seen that the dip directions of the respective joint sets are significantly different. This is due to the fact that the rotation (and resulting dip direction) of the 3D model was not calibrated with a real-life tunnel. However, this did not influence the possibility of identifying the correct values, since the measurements taken in VR could still be compared to the baseline values coming from VR.

Based on the questionnaire, it was proven that the Aalto staff was experienced with the average score reflecting tunnel mapping practice of 3.09 compared to 1.35 reported by students during the first VUTE experiment.

Results show that the changes that were implemented to the software between the two experiments have enhanced the system. This was reflected by an increase in usability by 10.02 points (from 72.25 to 82.27). Moreover, when compared with the usability score database created by Sauro (2011) the second iteration of VUTE has been placed in the 90th percentile among over five thousand tested computer systems. Furthermore, the learnability of the system has improved by 9.77 points, raising from 72.50 to 84.09. This shows that the second iteration of the VUTE software was perceived as easier to learn.

When comparing the list of issues and proposed changes reported by the Aalto staff with the one provided by students, it can be clearly seen that the four selected issues (imprecise answer inputting, too small VR area, VR causing nausea and VR area not reflecting the size of the real room) were successfully resolved.

The conclusions listed above allowed to decide to proceed to the next stage of the thesis – assessing the overall results of both tests.

5. Results of VUTE feasibility study

Described in this chapter are the overall results of the VUTE feasibility study which included two experiments – one involving 20 students from Engineering Geology course and the second one 11 members of the staff of Aalto University.

5.1. Results of the rock wall measurements

Total of 83 measurements was taken by the 20 participants during the VR tunnel visit, each measurement containing four parameters describing a joint set – its dip and dip direction, joint spacing and Joint Roughness Coefficient. During the real-life visit, a similar number of 78 measurements was reported. To get a quick, high-level overview of the recorded measurements, values provided by the students were plotted along with the baseline values assessed with help of the Aalto staff. Figure 41 shows the resulting stereoplots created with Stereonet software for both the visits.

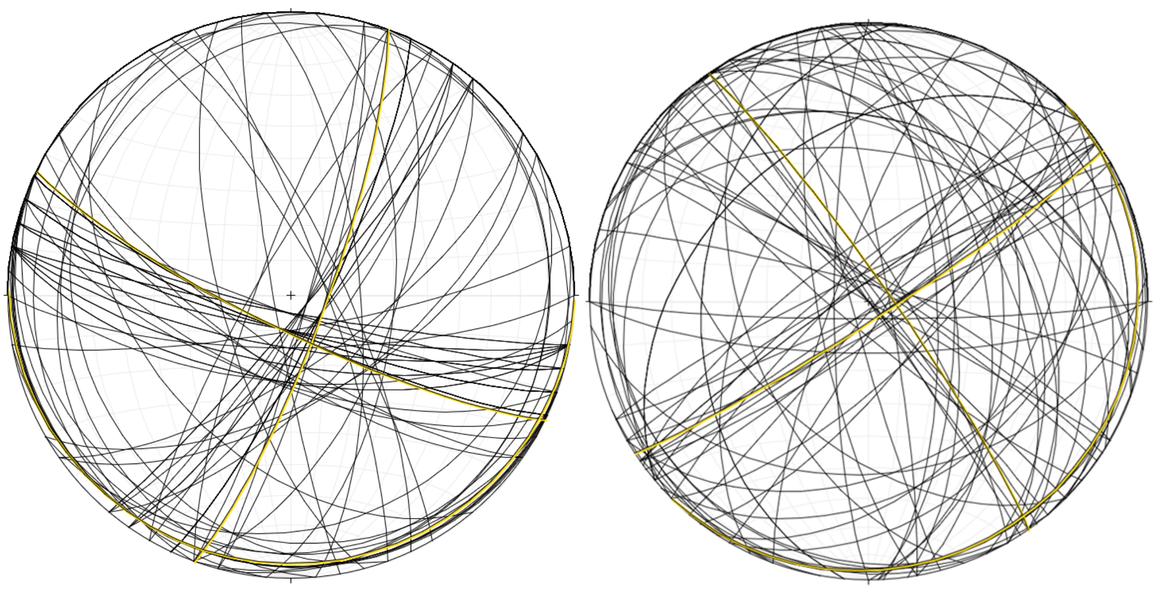


Figure 41 Measurements taken by students in VR (on the left) and in the real-life tunnel (on the right) with the baseline values marked in yellow

It can be clearly seen that the answers in real-life (right stereoplot) are significantly more chaotic than their VR counterparts. However, in order to precisely assess which approach to learning resulted in better answers, the measured values of Joint Spacing and JRC had to be taken into account. Therefore, a grading system was created and is described below.

5.1.1. Grading system

Both the measurements taken in VR and in the real-life were graded using the same algorithm. However, as stated before, the position (rotation) of the 3D model of the wall was not precisely calibrated with the position of the real-life wall. Therefore, the answers were compared to their respective baseline values: VR answers with assessed VR reference values and real-life with real-life.

The main idea of the grading system was that a measurement was marked as correct only when it was within a range of ± standard deviation of a parameter from its respective baseline value. This range was later referred to as the "error range". If a user described the spatial position of a joint set correctly (both the measured dip and dip direction are within the error range from the baseline values) she/he was given two points (one each for correct measurement of the dip and dip direction). Additional points were awarded for a correct reading of the Joint Spacing and the Joint Roughness Coefficient. Maximum four points could be received for a correctly distinguished and described joint set, with the grand total of 12 points (three joint sets times the maximum four points per joint set). In case of a situation where a user had measured parameters of the same joint set two or more times, the answer resulting in more points was accepted as the final answer. The flowchart representing the grading system can be seen in Figure 42.

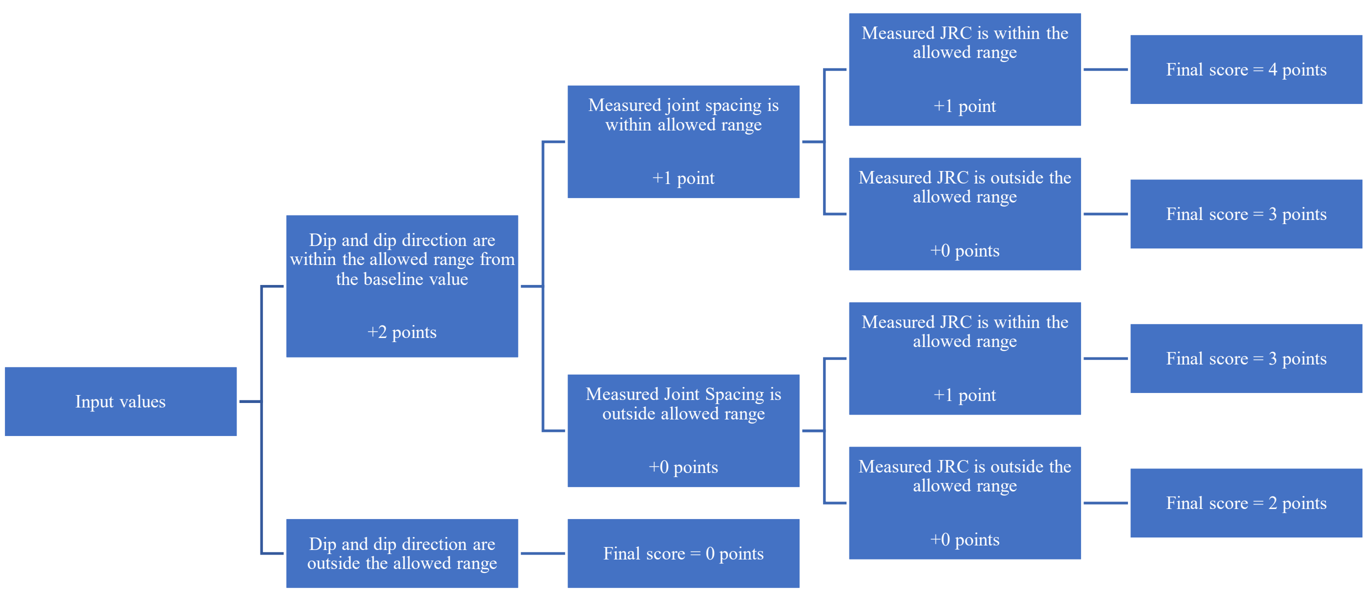


Figure 42 Flowchart of the algorithm used to grade the answers of the students

Based on the described approach the error ranges were calculated for each parameter, of each joint set in VR and in the real life. The values are presented in Table 16.

Table 16 Error ranges calculated for all four parameters in VR and in the real-life

	Joint set	**Dip**	**Dip Direction**	**JS [cm]**	**JRC [-]**
VR	JS1	80°±3°	110°±4°	21±8	6 ±2
	JS2	80°±4°	205°±5°	18±10	8 ±2
	JS3	5°±2°	180°±10°	9 ±2	6 ±3
Real-life	JS1	84°±3°	55°±4°	22 ±8	5 ±2
	JS2	85°±4°	147°±5°	21 ±10	6 ±2
	JS3	6°±2°	135°±10°	8 ±2	5 ±3

In the next step, with the use of the described algorithm along with the stated error ranges, the total amount of points scored by students was calculated and is shown in Table 17.

Table 17 Amounts of points assigned for correct rock wall measurements of each of the joint sets in the VR VUTE system and during the real-life tunnel visit

	Joint Set 1	**Joint Set 2**	**Joint Set 3**	**TOTAL**
VR VUTE System	19	8	0	**27**
Real life tunnel visit	0	6	5	**11**

In total, the participants of the study were able to obtain on average 16 points more when using the VR for taking the rock wall measurements, than when doing the same task in the real-life. When comparing the number of points that each user was able to achieve it was found that out of 20 people: three did better in the tunnel, eight did better in VR and nine did equally fine in both situations.

Moreover, when compared the Group A which first performed the task in VR and later in the tunnel, scored a larger amount of points than the Group B which followed the reverse order (14 vs 13 points). This shows that even though the second group had the chance to practice in the actual tunnel, they did not perform in VR better than Group A.

Furthermore, to verify whether the reported advantage of the VUTE system was statistically significant an average paired difference t-test was performed. Firstly, the hypotheses were stated:

$H_0: \mu_0 = 0$ Based on the sample data, the reported VR score is not significantly greater than the one obtained in real-life;

$H_1: \mu_0 \neq 0$ Based on the sample data, the reported VR score is significantly greater than the one obtained in real-life;

Later the number of points obtained by each user in the actual tunnel was subtracted from his/her score in the VR. Later the mean value of the differences was calculated along with the standard deviation. Based on those the value of the standard error was estimated and used to determine the tests statistics t. Due to the fact that the goal of the test was to verify whether the score in VR was significantly better than in real-life (and not whether it was significantly different) the p-value was estimated in Microsoft Excel for right-tailed Student's t-distribution using the T.DIST.RT function. The results of the t-test are shown in Table 18.

Table 18 Results of the average paired difference t-test performed for the grades achieved by the users in VR and in the real life

User ID	Score in VR	The score in the tunnel	Difference
1	2	2	0
2	0	2	-2
3	0	0	0
4	2	0	2
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	3	-3
10	0	0	0
11	3	0	3
12	4	0	4
13	3	0	3
14	0	2	-2
15	3	2	1
16	0	0	0
17	3	0	3
18	3	0	3
19	0	0	0
20	4	0	4
		Mean	0.800
		St. dev	2.016
		St. error	0.451
		t-value	1.775
		p-value	0.046

When compared, the calculated probability value $p = 0.046$ is lower than the assumed significance level $\propto = 0.05$. This shows that there is enough evidence to disregard the null-hypothesis and conclude that the average score difference is statistically significant and was a random outcome.

5.2. Differences between the VR and the real-life

To directly measure the disparities between the VR and the real-life, namely the differences between perceiving distances, the students were asked to estimate the length of three lines (with 0.5 m precision) both in the VUTE VR software and in the tunnel – one vertical and two horizontal as shown in Figure 43. The corresponding lengths were equal in VR and in the real-life.

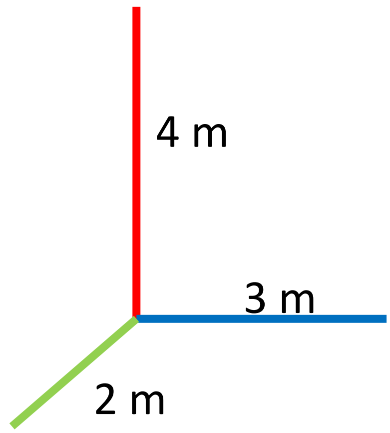


Figure 43 Line positions and actual lengths

In VR the estimations given for the 4m long vertical red line ranged from 3 to 5 m with an average of 4.25 m, median of 4.5 m and standard deviation of answers 0.51 m. In the tunnel, the values ranged from 3.5 to 6 m with an average of 4.58 m, median of 4.5 m and a standard deviation of 0.62 m. The average estimation error (defined as the module of the mean difference between the actual and estimated lengths) was 0.25 m for the VR and 0.58 m for the tunnel. The specific values reported by each user are depicted in Figure 44.

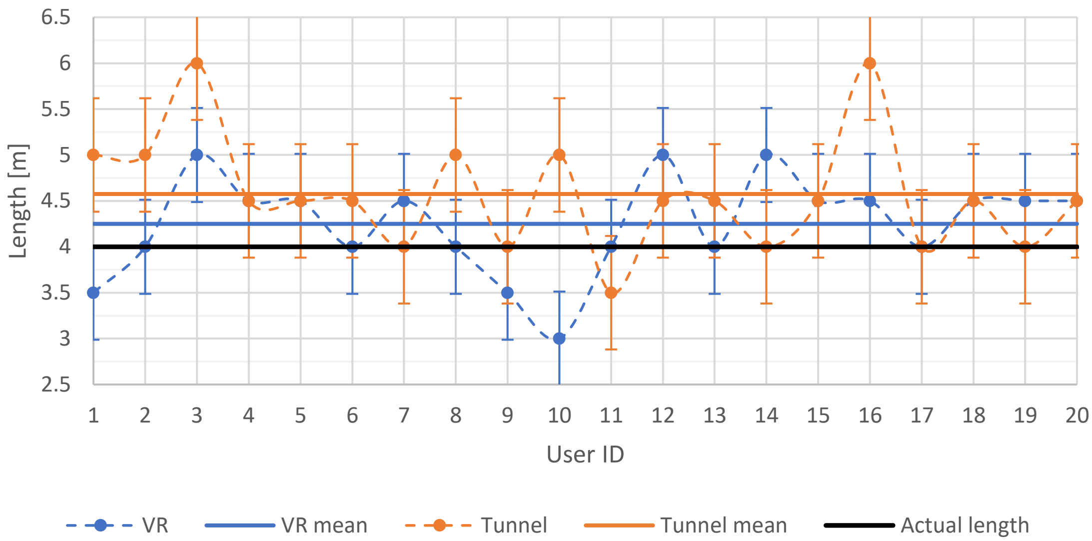


Figure 44 Results of users' estimations of the length of the vertical red line (L1=4m) in VR and in the tunnel. Error bars represent the standard deviation of the answers

Estimations for 3 m long blue line (horizontal parallel to horizon) were ranging in VR from 2 to 4 m with an average of 2.8 m, mode of 2.5 m and standard deviation of 0.48 m. In the tunnel, the reported estimations reached values from 2 to 4 m, a mean of 3.05 m, mode of 3 m and standard deviation of 0.5 m. The average estimation error was 0.20 m for VR and 0.05 m for the tunnel, as shown in Figure 45.

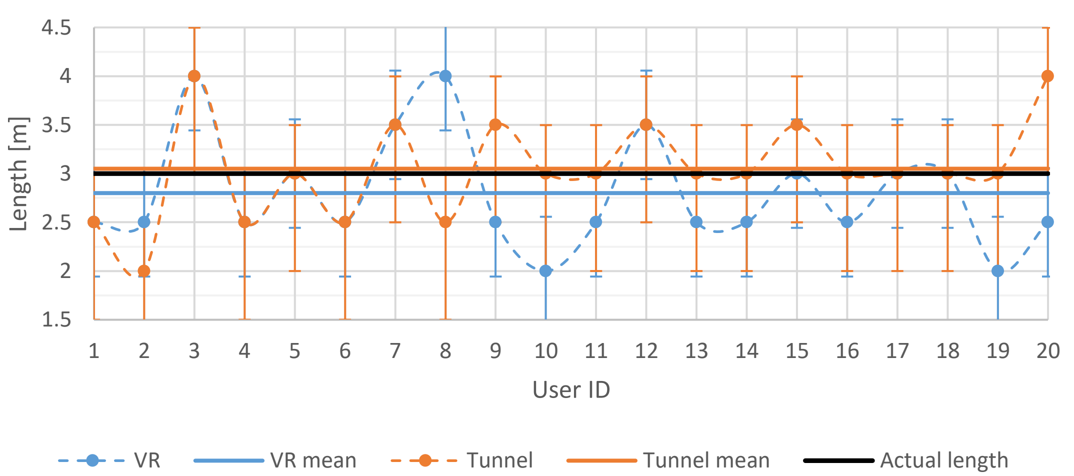


Figure 45 Results of users' estimations of the length of the horizontal blue line, parallel to the horizon (L2=3 m) in VR and in the tunnel. Error bars represent the standard deviation of the answers

In VR the green horizontal line (perpendicular to the horizon and 2 m long) was estimated to be from 1 to 3 m long, 1.83 m on average, with the mode of 1.5 m and standard deviation of 0.48 m. In the tunnel, the minimum estimated length was 1.5 m and the maximum was 3 m with a mean value of 2.13 m, median of 2.0 m and the standard deviation of 0.47 m. The average estimation error was 0.18 m for VR and 0.13 m for the tunnel. Figure 46 shows the exact values given by the 20 users of VUTE software. The average estimation error (for all three lines) among the participants of the experiment was 0.21 m in VR and 0.25 m during the real-life tunnel visit.

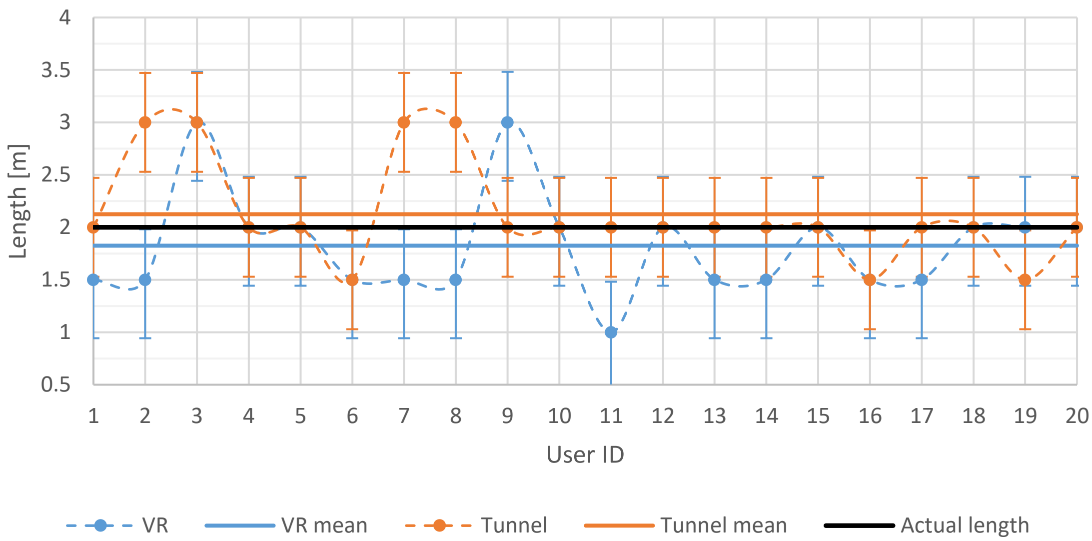


Figure 46 Results of users' estimations of the length of the horizontal green line (L3=2 m), perpendicular to the horizon, in VR and in the tunnel. Error bars represent the standard deviation of the answers

Differences between the reported lengths in VR and in real life were testes for statistical significance using the average difference paired t-test. Firstly, for all three lines, the values estimated in VR were subtracted from their real-life counterparts resulting in three datasets. Afterward, following hypotheses were stated:

$H_0: \mu_0 = 0$ Based on the sample data, the reported length differences are not significantly different from zero;

$H_1: \mu_0 \neq 0$ Based on the sample data, the reported differences are significantly different from zero.

The next steps were identical as during the test for significance of time differences and included calculating for each of the three datasets: the mean value, standard error, test statistic, and the probability value. The numerical results are shown in Table 19.

Table 19 Values of parameters for all three datasets, used for testing the null-hypothesis using the paired t-test

Dataset	**L1**	**L2**	**L3**
Mean	0.33	0.25	0.30
σ	0.80	0.64	0.66
S_e	0.179	0.143	0.147
t	1.82	1.75	2.04
p	0.085	0.096	0.055
α		0.05	

In all three cases the p-value was larger than the assumed significance level $\alpha = 0.05$ and thus the null-hypothesis that people perceive lengths in VR the same way they do it in real life was not disproven. Moreover, in an external study by Liu (2015) it was reported that, when using HTC Vive headset, the reported perception of scale and distance is the same in VR as in the real world.

To indirectly assess the dissimilarities between the VR experience and the actual tunnel visit a list of written answers to a question about the differences were collected. 15 out of 20 participants (5 did not respond to the question) provided a list of 36 aspects, which were arranged into 21 groups by the author. The most common answer, mentioned by 53% people (8 out of 15) was “lack of haptic feedback in VR”. The answer referred to the fact the VUTE system did not include a function to create an illusion of touch when coming in contact with objects inside the virtual reality. This forced the users to rely on their sight when placing the VR tools against the surface of the model. The second most reported difference (3 out of 15 users, or 20%), was the blurriness of the rock wall model when compared to reality. This answer was directly linked to the low resolution of the display used in the HTC Vive headset. The rest of the issues were mentioned by two or fewer people. The full list is presented in Appendix 4, Table 23.

5.3. Other results

5.3.1. Personnel-efficiency of VR

Another of the advantages of using the VR systems for learning is their potential to decrease the number of the teaching staff involved in it and the time they are required to devote to the task. During the VUTE study, it was found out that for the VR tunnel visit only one supervisor was required for no more than a couple of minutes required for instructing the user about the basics of the VR technology and the following system set-up. On the other hand, the tunnel visit required a supervision of two members of the Aalto staff for its whole duration and was proceeded by a series of preparations (involving setting up the tunnel illumination, gathering the measurement tools, etc.) that involved work of one of the employees. This shows that once created and set-up, the VR system requires very little involvement, unlike the real-life tunnel visit, enabling the employees of the university to devote their time to higher teaching purposes.

5.3.2. Personal preferences of the users

When asked directly about their preferences regarding the way of learning the tunnel mapping, and the approach that allowed them to learn more, the participant's answers were similar. The visit to the actual tunnel was the preferred way of learning for 11 users (55.0% of the total) with the most often reported reason being that "VR should be an addition to the actual tunnel visit" rather than the standalone approach. Similarly, 12 (60%) students admitted that in their opinion tunnel visit allowed them to learn the subject better because the real visit allowed consulting with peers and with the lecturer. Six users (30%) answered that they liked both ways of learning equally, but only four (20%) reported that they have learned as much in VR as in the tunnel. Only three (15%) participants favored learning in VR and the same amount stated that such an approach allowed them to learn the most. Detailed responses of the users can be found in Appendix 4.

5.3.3. M!EDU

Leveraging the results from the VUTE feasibility study, the "M!EDU – Mining Education and Virtual Underground Rock Laboratory" project has been granted funding from Aalto Online Learning - A!OLE to proceed from seed to pilot stage. The received sum of 60'000 EUR was partially used to purchase, for use in teaching and training, six Virtual Reality stations with specifications presented in Table 20.

Table 20 Hardware specifications of the purchased VR stations

CPU	**Intel Xeon E5-1650V2 / 3.5 GHz**
GPU	ASUS Geforce GTX 1080 Ti Turbo 11GB
Memory	32 GB RAM
VR headset	HTC Vive + HTC Vive Pro headset

Moreover, when evaluating the feedback from the participants of the VUTE study the low resolution of the VR display was identified as one of the most commonly reported issues. Based on that a decision was made to replace the default headset provided with HTC Vive VR set with HTC Vive Pro, an upgraded version which boasted a 73% higher overall resolution.

6. Discussion of results and conclusions

6.1. Discussion of results

6.1.1. The effectiveness of learning through Virtual Reality

To verify or disprove the hypothesis stated in the very beginning of the study, it was necessary to test whether the users were able to produce measurements in VR that was at least as good as those taken in real life. This would prove that in terms of the learning outcomes the VUTE system was an applicable alternative to the real-life tunnel visits for the for practicing taking rock wall measurements.

What the study found was that the students in VR, using a scanned model of a 3D wall have obtained on average 145% more points than when taking the measurements in real-life. Moreover, when the differences in amount of points achieved by a user were tested, it was proven that for the 95% confidence interval they are statistically significant, or in other words they can be used to model the difference in the whole population and were not the result of a sampling error nor a random occurrence. Furthermore, when different configurations were tested the Group A (that first performed the measurements with use of VUTE and then in the tunnel) scored even better in VR than the Group B that followed the reverse order. This shows that the fact of practicing the task most likely did not have an influence on the final performance.

Search for a similar study has shown that there does not exist another study examining the feasibility of replacing real-life education in mining and/or geology with virtual reality. Therefore, this thesis was most likely the first one to do that and to prove that when it comes to taking rock wall measurements, VR creates the potential for its users to produce results better than in real life. This definitive result enables other researchers to further investigate the potential to replace troublesome/complicated practical exercises with Virtual Reality systems.

On the other hand, even though the reported difference in the number of correct measurements were meaningfully larger in VR, in both cases the overall performance of the participants was very low. Moreover, this type of measurements is very subjective and prone to error especially for the inexperienced users, which can be clearly seen when looking at the stereoplotted dip and direction measurements. Therefore, there exists a possibility that the poor performance of the users might have had an unforeseen impact on the outcome of the study. Furthermore, grading of the measurements was based on the baseline values, which were produced by people and thus prone to human error. This shows that in such case there exists a need to develop a less subjective and human dependent approach to assessing the rock wall parameters.

6.1.2. The efficiency of learning through Virtual Reality

To assess the learning efficiency of the VUTE system a need to compare the time required to perform the task in both settings (VR and real-life) was recognized. The rationale behind it was that a situation where setting-up and taking measurements in VR takes substantially longer than in real-life would give a clear sign that the VUTE system is struggling with efficiency and might not be feasible.

However, when tested the results have shown that the VUTE system has not only the capability to decrease the time required to take the rock wall measurements (2.64 minutes or 12.5% decrease) but also to significantly cut the time required for preparation to the exercise (17.2 minutes or 92.2% decrease). This shows that the VUTE system allows to significantly cut the time wasted on the set-up allowing the user to dedicate more time to actual learning which he can do more effectively in VR.

Moreover, in the study correlations were assessed between the time spent on the measurements and different factors, that might have influenced the duration of the exercise and bias the measurements biased the measurement, such as previous experience with the VR technology, prior mapping experience, FPS gaming habits and perceived usability and learnability of the system. In all cases, the correlation was found to be moderate at best.

When trying to find relatable research focusing on study of time gains/losses resulting from realizing education/training in VR, the author discovered that the closest study, VR-CHEM Master's (Krupakar, 2017) which found that modeling complex 3D structures with use of VR was more time consuming, was focused on the shift from PC 2D interface to 3D VR. Therefore, based on that it can be clearly seen that the VUTE experiment, by comparing the tasks done in VR by doing them in real-life is unique in this aspect.

On the other hand, the reported specific amount of time saved regarding set-up was characteristic to the particular case of the Aalto University and might differ even when comparing the same group on different days. However, the underlying idea to prove that the amount of time necessary for the set-up of VR is visibly shorter compared to any exercise that must be performed in in-situ or other unusual conditions has been realized.

Then again, the differences between the duration of the exercise (T2+T3 VR vs real-life) were proven to be statistically significant, or in other words not likely to have occurred randomly or due to a sampling error and can be used to characterize the whole population of people that would use the VUTE system for taking rock wall measurements.

However, in the examined weak correlations that might have had an influence on the measured T2+T3 times, when tested have been proven to be statistically insignificant and might have occurred randomly or due to a sampling error.

6.1.3. Differences between the VR experience and the real-life tunnel visit

The potential issue with the VUTE system was that in case of major differences between VR and the real-life the results (both the time differences and the graded measurements) obtained with the two approaches might have been not comparable directly. Such a problem could have occurred for example due to the VR model is very low quality and impossible to correctly measure.

The assessment of the differences was split into two categories: direct, measured numerically and indirect focused evaluated based on written feedback. The direct measurement was focused on assessing the differences in depth perception between the VR and the real-life. The study has shown that in the case of VR the average error in estimating the length was 0.21 m, while in the real-life the result was 0.25 m. This very small difference or even lack of it, when considering that the lengths were estimated only visually, is a significant result when considering that the exercise was focused mainly on measuring spatial parameters and identifying spatial relationships, such as surfaces being parallel or not. Moreover, this thesis is one of the first, if not the first study, to investigate the differences in depth perception between VR and the real-life on a group of multiple people. The only other study found by the author that was related to this subject conducted its tests only on one test subject.

On the other hand, when tested for the statistical significance at the 95% confidence interval, the results were not able to disprove the null-hypotheses (one for estimation along each axis) stating that the mean difference between the reported lengths is 0. Therefore, there exists a possibility that the reported lack of differences was a result of randomness.

In case of the indirect measurement, a list of differences stated in a form of a written answer to an open question was analyzed. The main, most often reported disparities were the lack of haptic feedback in VR and lack of immersion of the scene resulting from a low resolution of the used VR headset. After reviewing the feedback and assessing that the users of the VUTE system performed better in terms of the quality of measurements, in VR than in the real-life a conclusion can be drawn that those two reported differences were not significant from the learning point of view.

6.1.4. Usability and learnability of the VUTE system

To show that the results obtained in VR, mainly the rock wall parameter measurements and time measurements, are comparable to those from the real world it was necessary to test whether the system was usable, learnable and free from significant issues.

Based on the SUS questionnaire answers it was found that, according to its twenty users, the first version of the system already can boast good usability having scored on average 72.25 points. Moreover, the learnability of the system was assessed as good as well reaching the average score of 72.50 points. The second iteration of the VUTE system was graded by its eleven new users and the following was found: the usability has increased on average by 13.9% to 82.27 points, while the learnability improved by 16.0% reaching 84.09. The reported usability scores show an important result since according to Bangor et al. (2009) any system with SUS score above 70 do not have any significant usability issues that might cause concerns.

Comapring the achievied usability score to a similar, already the first version of the VUTE system scored 2.5 points higher (72.5 vs 70.0) than the coal mine training system developed by Grabowski and Jankowski (2014) which utilized the Development Kit of Oculus Rift together with Razer Hydra controller. Furthermore, a study conducted by J. Sauro (2011), based on thousands of SUS measurements, provides a benchmark for assessing how the specific SUS score places in relation to other systems. The chart presented in Figure 47 shows that the SUS score of 72.25 places the first version of VUTE between the 60th and 63rd percentile when compared to the other computer systems. In case of the second iteration of the software the 82.27 score positions it between the 90th and 93rd percentile.

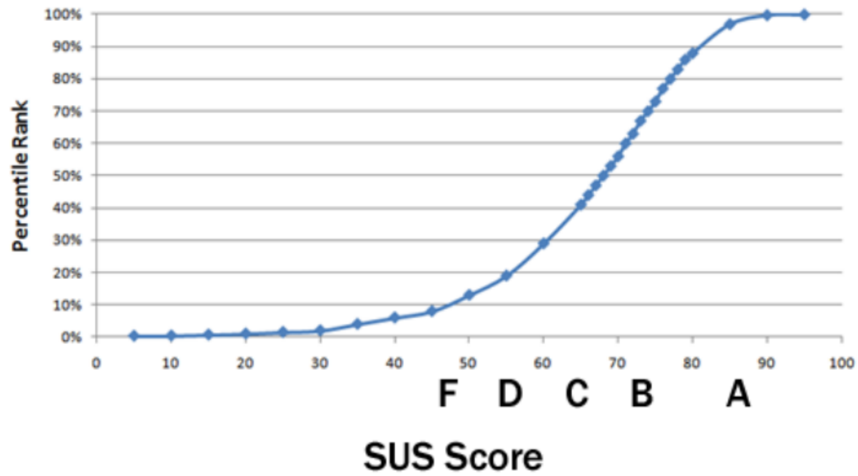


Figure 47 SUS score ranking based on a study conducted by J. Sauro Source: Sauro, 2011

The reliability of the System Usability Scale results can be deemed as high because SUS is very easy to use the tool, which has been tested in countless studies (the study by Sauro alone has analyzed over five thousand of them) and is now considered as the industry standard. On the other hand, the SUS score was designed to test the traditional 2D computer systems and the author did not find any studies on its reliability in case of the 3D VR systems.

6.2. Conclusions

The high usability and learnability of the system (82.27 and 84.09 points on SUS respectively), together with the fact that the differences in length perception were proven to be small (0.29 m on average) and statistically insignificant support the hypothesis stating that:

The created VUTE system is free from significant issues and replicates the real-life tunnel visit in a way that allows for their direct comparison

Therefore, having assessed that both approaches are directly comparable further results can be considered. Those clearly state that the VR system has been able to decrease the time spent on the exercise. The average time required to prepare was lowered by 17.17 minutes, resulting in 92.2% decrease in duration from 18.62 to 1.45 minutes. Moreover, the time necessary to perform rock wall measurements was 3.77 minutes or 16.9% shorter dropping from 22.3 to 18.53 minutes.

On the other hand, when using the VUTE software were given for their measurement a total of 27 points, while in the real-life tunnel the score was 11, 59.26% lower – a difference that was proven to be statistically significant. In result, it was possible to confirm the hypothesis stating that:

The developed virtual reality software reduces the time spent on the rock wall mapping exercise while maintaining the same or better learning outcomes as the real tunnel visit

Considering that both hypotheses were tested and stand true, it is possible to state that the main goal of the thesis was met, and that the VR technology has been proven to be a feasible replacement of the regular way that the rock wall mapping is taught at the Aalto University.

The literature search has shown that the use of virtual technology in mining is almost none. However, the technology, while still being fresh, can provide a range of benefits to the industry. One of the most crucial ones would be the possibility to replace the hazardous workplace with a safety of virtual reality, while at the same time maintaining. With the use of 3D scanning, the previously inaccessible stopes would be fully safe explorable for the mine staff. Realistic safety training could include a possible scenario in any part of the mine, replayable as many times and as often as necessary without disrupting the everyday operations.

To summarize, this dissertation has proven that the VR technology has the potential to benefit the mining industry, especially on the field of training, and that this thesis should be treated as one of the first steps towards investigating and realizing its full potential.

7. Recommendations and path forward

Even though, the results have shown that the VUTE VR software is a feasible replacement for the real-life tunnel visit when teaching rock wall mapping, the author wants to point out to opinions and reported preferences of its users, which contrast with the outcome of the study. The students, in majority have reported that in their opinion they prefer and have been able to learn more about tunnel mapping in real-life. This discrepancy was a surprising finding to the author and has led him to believe that more research is required to be able to ultimately state that the VR systems are better for teaching taking rock wall measurements than the real life. For now, the ultimate recommendation of the author would be to use the VUTE and similar software to serve as augmentation to the regular teaching, rather than the replacement.

During the development, the author had the possibility to test various technologies and software to make the VUTE happen and would like to provide the following recommendations to anyone willing to create and test the VR learning tool as well.

The PC with the specifications mentioned in the thesis was fully capable of running the VR software including the scenes containing models made from 2+ million polygons. With the Nvidia GeForce RTX 20XX GPU becoming available after the experiment phase of the thesis, the boundaries can be pushed further, and even more detailed models can be used in the simulations.

If using the VisualSFM and the recommended programs for creating and editing the 3D scans, the author suggests utilizing the file formats recommended in the thesis to save the disc space, as the models are prone to being very large.

Unity has proven to be a suitable 3D environment for developing VR systems. However, for creating the system, the non-scripting Playmaker addon has shown to be cumbersome and very inefficient. This has proven that even though, it is possible to create such a software without coding skills, this approach it might require substantially more time.

On the other hand, if the 3D scans created with photogrammetry are not the part of VR or the colors of the scanned object do not have to be replicated, Unreal Engine 4 might be a fully functional replacement for Unity. One of the advantages of UE4 is native support for the non-scripting development system, which is available for free. Therefore, both engines are suitable for creating the VR systems and the decision should be made based on the personal preferences of the creators and/or availability of the licenses.

System Usability Scale has proven to be a fantastic tool for assessing the usability of a computer system – easy to prepare (ready format of questionnaires) and process. Moreover, because it is an industry standard used in countless studies, it gives the possibility to easily compare it to other similar systems.

When looking at the feedback provided by the users, the low pixel density of the display of the VR headset has greatly decreased the user satisfaction. Therefore, the author suggests that along with new iterations of the headset, better resolution headgears should be tested.

References

[1] Bangor A., Kortum P., Miller J., 2009. “Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale” JUS Journal of Usability Studies Vol. 4, Issue 3, May 2009, pp. 114-123

[2] Barton, N.R. 1973. “Review of a new shear strength criterion for rock joints” Engineering Geol. 7, 287-332.

[3] Barton, N.R., Choubey, V., 1977. “The shear strength of rock joints in theory and practice” Rock Mechanics 10(1-2), 1-54.

[4] Bowman D. A., McMahan R. P., 2007. “Virtual Reality: How Much Immersion is Enough?” Computer, Volume: 40, Issue: 7, July 2007

[5] Brooke J., 1986. “SUS - A quick and dirty usability scale”

[6] Caballero E., Dzugala M., 2018. “KARMO Mechanical Properties of Rock Joints Guide to Close Range Photogrammetry”

[7] CapturingReality, 2018. “Germany's last coal mine in VR” http://www.capturingreality.com/Article-Realities Retrieved on 10 Nov 2018

[8] Daneshmand M., Helmi A., Avots E., Noroozi F., Alisinanoglu F., Arslan H. S., Gorbova J., Haamer R. E., Ozcinar C., Anbarjafari G., 2018. “3D Scanning: A Comprehensive Survey”

[9] Dede C., 2009. “Immersive Interfaces for Engagement and Learning” Science, Vol. 323, 2 January 2009

[10] Fekete S., Diederichs M., Lato M., 2009. “Geotechnical applications of lidar scanning in tunneling” ROCKENG09: Proceedings of the 3rd CANUS Rock Mechanics Symposium, Toronto, May 2009

[11] Grabowski A., Jankowski J., 2014. “Virtual Reality-based pilot training for underground coal miners” Safety Science 72:310–314 February 2015

[12] Grajewki D., Gorski F., Hamrol A., Zawadzki P., 2015. „Immersive and Haptic Educational Simulations of Assembly Workplace Conditions” Procedia Computer Science 75 (2015) 359 – 368

[13] HexagonMining, 2018. “Hexagon adds virtual reality to improved mine planning solution” http://www.hexagonmining.com/resource/press-releases/hexagon-adds-virtual-reality-to-improved-mine-planning-solution Retrieved on 1 November 2018

[14] Howard, Ian P., Rogers, Brian J., 1995. “Binocular Vision and Stereopsis” Oxford University Press

[15] Hui Z., 2017. “Head-mounted display-based intuitive virtual reality training system for the mining industry” International Journal of Mining Science and Technology 27(4) May 2017

[16] ISO 9241, 2018. “Ergonomics of human-system interaction”

[17] ISO/IEC 25010, 2011. “Systems and software engineering -- Systems and software Quality Requirements and Evaluation (SQuaRE) -- System and software quality models”

[18] Kalawsky R.S., 1993. “The science of virtual reality and virtual environments: a technical, scientific and engineering reference on virtual environments” Addison-wesley Workingham

[19] Kolasinski, E. M., 1995. “Simulator sickness in virtual environments” ARI Tech. Report 1027. Army Research Institute for Behavioral and Social Sciences”

[20] Krupakar D., 2017. “VR-CHEM Developing a Virtual Reality Interface for Molecular Modelling” Master’s thesis developed at Aalto University’s Department of Media

[21] Le Q. H., Lee J. W., Yang S. Y., 2017. “Remote control of excavator using head racking and flexible monitoring method” Automation in Construction Volume 81, September 2017, Pages 99-111

[22] Liu Y., 2015. “Is VR True to Scale? Experiments Say Yes” https://blog.irisvr.com/blog/category/is-vr-true-to-scale-two-scientific-experiments Retrieved on 4 August 2018

[23] Llorach G., Evans A., Blat J., 2014. “Simulator Sickness and Presence using HMDs: comparing use of a game controller and a position estimation system” Interactive Technologies Group, Universitat Pompeu Fabra Barcelona, Spain

[24] Mqworld, 2018. “PDAC 2018 and MacLean Mining Innovation: Virtual Reality Bolter Training Tool Showcase” http://www.mqworld.com/2018/03/05/pdac-2018-maclean-mining-innovation-virtual-reality-bolter-training-tool-showcase Retrieved on 3 November 2018

[25] Niehorster D. C., Li Li, Lapper M., 2017. “The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research” i-Perception May-June 2017, 1-23

[26] Patel N., 2018. "Unity vs Unreal Engine? No more Confusion for Game development" Medium https://medium.com/@patelnisha121/unity-vs-unreal-engine-no-more-confusion-for-game-development-4261668c15d7 Retrieved on 3 April 2018

[27] Pavlidis G., Koutsoudis A., Arnaoutoglou F., Tsioukas V., Chamzas Ch., 2007. "Methods for 3D digitization of Cultural Heritage" Journal of Cultural Heritage 8 (2007) 93e98

[28] Polycount, 2018. "Polycounts in next gen games thread!" http://polycount.com/discussion/141061/polycounts-in-next-gen-games-thread Retrieved on 17 June 2018

[29] Sanchez J. L. G., Zea N. P., Gutierrez F. L., 2009. "From Usability to Playability: Introduction to Player-Centred Video Game Development Process" Human Centered Design, HCII 2009, LNCS 5619, pp. 65–74, 2009.

[30] Sauro J., 2011. "A Practical Guide to the System Usability Scale: Background, Benchmarks, & Best Practices," Denver, Published by Measuring Usability LLC

[31] ScienceDirect, 2018. "Why should I use ScienceDirect? " https://service.elsevier.com/app/answers/detail/a_id/10511/supporthub/sciencedirect/kw/amount/ Retrieved on 20 November 2018

[32] Shapeways, 2018. "Polygon Reduction with Meshlab" https://www.shapeways.com/tutorials/polygon_reduction_with_meshlab Retrieved on 18 June 2018

[33] Snavely K. N., 2008. "Scene Reconstruction and Visualization from Internet Photo Collections" Doctoral dissertation, University of Washington Graduate School

[34] Spence I., Feng J., 2010. "Video games and spatial cognition" Review of General Psychology, 14(2), 92–104

[35] Stone, A., 2017. "How Virtual Reality Is Changing Military Training" https://insights.samsung.com/2017/07/13/how-virtual-reality-is-changing-military-training/ Retrieved 01.09.2018

[36] Szydlowska, M., 2016. "Systematic review of georisk in underground hard rock mines" Master's thesis published by Aalto University on 28.06.2016

[37] Tashiro J. S., Dunlap D., 2007. "The Impact of Realism on Learning Engagement in Educational Games"

[38] Tibbett, J., 2016. "UNSW Mining Engineering has created the Mining Education Australia (MEA) Mineral Awareness VR experience to take students on a virtual journey to explore the origins of the mineral ingredients required to make a smartphone" http://www.mea.edu.au/virtual-reality Retrieved on 8 November 2018

[39] Unity, 2018. "Unity User Manual/Physics/Physics Overview/Colliders" https://docs.unity3d.com/Manual/CollidersOverview.html Retrieved on 12.05.2018

[40] Valdez M., Ferreira C., Martins M., Barbosa F., 2015 "3D virtual reality experiments to promote electrical engineering education" 2015 International Conference on Information Technology Based Higher Education and Training (ITHET)

[41] Vive, 2018. "VIVE Ready Computers" https://www.vive.com/us/ready/ Retrieved on 4 May 2018

[42] Westoby M. J., Brasington J., Glasser N. F., Hambrey M. J., Reynolds J. M., 2012. "'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications" Geomorphology Volume 179, 15 December 2012, Pages 300-314

[43] Wong L. N. Y., 2015. "Determination of normal joint spacing from apparent joint spacing measurements" Global View of Engineering Geology and the Environment – Wu & Qi (eds)

[44] Zielinski D. J., Kopper R., McMahan R. P., Lu W., Ferrari S., 2013. "Intercept tags: enhancing intercept-based systems" In Proc. VRST 2013, pp. 263–266. ACM, 2013

Appendix 1 VR questionnaire

The Virtual Reality Experience Questionnaire

Name: ____ **Date:** ___________

Age: __________ **Gender:** Male[ ] Female[ ] Would rather not tell [ ]

Group: A [ ] B [ ]

1. Have you ever used Virtual Reality **before**?

No [ ] Yes, once or twice [ ] Yes, a few times [ ] Yes, many times [ ]

2. Do you play FPS games e.g. shooters on your computer/console?

Never or almost never [ ] Yes, monthly [ ] Yes, weekly[ ] Yes, daily [ ]

3. Do you think that the Virtual Reality has helped you learn the subject better?
   1 is totally disagree and 5 is totally agree

   1 [ ] 2[ ] 3[ ] 4[ ] 5[ ]

Answer the questions on a scale of 1 to 5, where **1 is totally disagree** and **5 is totally agree**

	1	2	3	4	5
I think that I would like to use VR frequently					
I found VR unnecessarily complex					
I thought VR was easy to use					
I think that I would need the support of a technical person to be able to use VR					
I found the various functions in VR were well integrated					
I thought there was too much inconsistency in VR					
I would imagine that most people would learn to use VR very quickly					
I found VR very cumbersome to use					
I felt very confident using VR					
I needed to learn a lot of things before I could get going with VR					

SEE THE OTHER PAGE!

What can we change in order to improve our VR software? Are there any things in the User Interface that we should change? Any other comments?

____

____

____

Appendix 2 Tunnel questionnaire

Tunnel Visit Questionnaire

Name: ____ **Date:** ____________

Age: __________ **Gender:** Male[ ] Female[ ] Would rather not tell [ ]

Group: A [ ] B [ ]

1. Have you ever done any tunnel mapping **before**?

No [ ] Yes, once or twice [ ] Yes, a few times [ ] Yes, many times [ ]

2. Do you think that the tunnel mapping has helped you learn the subject better?
   1 is totally disagree and 5 is totally agree
   1 [ ] 2[ ] 3[ ] 4[ ] 5[ ]

What can we change in order to improve our tunnel mapping exercise? Are there any things in the tunnel mapping that we should change? Any other comments?

____

Appendix 3 Final questionnaire

Final Questionnaire

Name: ____ **Date:** _____________

Age: ___________ **Gender:** Male[ ] Female[ ] Would rather not tell [ ]

Group: A [ ] B [ ]

1. Answer the questions on a scale of 1 to 5, where **1 is totally disagree** and **5 is totally agree**

	1	2	3	4	5
I feel confident with measuring the dip now					
I feel confident with measuring the dip direction now					
I feel confident with measuring the Joint Roughness Coefficient now					
I feel confident with measuring the joint spacing now					
I feel confident with identifying the joint sets now					

2. I **prefer** to learn tunnel mapping in:
   Virtual Reality [ ] The actual tunnel [ ] Both[ ] Neither [ ]

3. I answered XYZ in question 2, because:

____

____

4. I have **learned more** about tunnel mapping in:
   Virtual Reality [ ] The actual tunnel [ ] Both [ ] Neither [ ]

5. I answered XYZ in question 4, because:

____

____

6. I experienced nausea during the virtual reality exercise
   1 is totally disagree and 5 is totally agree
   1 [ ] 2[ ] 3[ ] 4[ ] 5[ ]

7. Which parts of the VR did you **like** the most? Name at least three

____

____

____

8. Which parts of the VR did you **dislike** the most? Name at least three

____

____

____

9. What were the main differences between the VR and the actual tunnel?

____

____

____

Appendix 4 VUTE first experiment results

Table 21 Results of the time measurements

Case	**VR**			**Tunnel**		
User ID/Time	T1 [min]	T2 [min]	T3 [min]	T1 [min[	T2 [min]	T3 [min]
1	0.62	3.52	4.65	18.62	5.33	21.78
2	0.75	3.18	12.18	18.62	5.33	21.78
3	0.58	4.83	12.18	18.62	1.53	17.65
4	0.40	3.92	14.32	18.62	1.53	17.65
5	0.98	7.17	17.33	18.62	5.33	21.78
6	1.18	5.62	6.93	18.62	1.53	17.65
7	1.20	6.62	12.37	18.62	1.53	17.65
8	0.90	4.97	13.77	18.62	1.53	17.65
9	1.62	5.63	11.03	18.62	1.53	17.65
10	0.97	9.08	20.23	18.62	5.33	21.78
11	6.67	6.63	10.87	18.62	1.53	17.65
12	1.15	5.98	15.02	18.62	1.53	17.65
13	1.15	4.95	11.65	18.62	1.53	17.65
14	1.33	6.57	10.87	18.62	1.53	17.65
15	2.02	5.38	11.17	18.62	1.53	17.65
16	1.62	6.90	12.63	18.62	1.53	17.65
17	1.82	6.13	12.05	18.62	5.33	21.78
18	1.95	11.42	13.68	18.62	1.53	17.65
19	0.93	5.78	12.62	18.62	1.53	17.65
20	1.12	7.68	13.05	18.62	1.53	17.65
MIN [min]	0.40	3.18	4.65	18.62	1.53	17.65
MAX [min]	6.67	11.42	20.23	18.62	5.33	21.78
Mean [min]	1.45	6.10	12.43	18.62	2.48	18.68
Median [min]	1.15	5.88	12.28	18.62	1.53	17.65
Mode [min]	1.62	-	12.18	18.62	1.53	17.65
Standard deviation	1.27	1.84	3.15	0.00	1.65	1.79
Variance	1.62	3.37	9.95	0.00	2.71	3.20

Table 22 Correlations between the duration of the exercise (T2+T3) and reported VR, FPS and tunnel mapping experience

User ID	**T2+T3 [min]**	**VR experience [-]**	**T2+T3 [min]**	**FPS exp. [-]**	**T2+T3 [min]**	**Mapping exp. [-]**	**T2+T3 [min]**	**Reported nausea [-]**
1	8.17	3	8.17	3	8.17	1	8.17	2
2	15.37	1	15.37	2	15.37	2	15.37	1
3	17.02	3	17.02	1	17.02	3	17.02	1
4	18.23	3	18.23	3	18.23	2	18.23	2
5	24.50	2	24.50	2	24.50	1	24.50	1
6	12.55	1	12.55	1	12.55	1	12.55	1
7	18.98	1	18.98	1	18.98	1	18.98	4
8	18.73	2	18.73	1	18.73	1	18.73	3
9	16.67	1	16.67	3	16.67	2	16.67	1
10	29.32	1	29.32	1	29.32	1	29.32	1
11	17.50	1	17.50	1	17.50	1	17.50	1
12	21.00	1	21.00	1	21.00	2	21.00	3
13	16.60	1	16.60	2	16.60	1	16.60	1
14	17.43	1	17.43	2	17.43	1	17.43	3
15	16.55	2	16.55	3	16.55	1	16.55	3
16	19.53	2	19.53	1	19.53	2	19.53	1
17	18.18	1	18.18	1	18.18	1	18.18	2
18	25.10	1	25.10	1	25.10	1	25.10	4
19	18.40	1	18.40	1	18.40	1	18.40	1
20	20.73	3	20.73	1	20.73	1	20.73	1
$r_{X,Y}$	-0.212		-0.421		-0.098		0.101	
t-value	-0.921		-1.968		-0.418		0.430	
p-value	0.369		0.064		0.681		0.672	
Significance level α	0.050		0.050		0.050		0.050	
Significance of the results	Insignificant		Insignificant		Insignificant		Insignificant	

Table 23 Grouped answers to the question "What were the main differences between the VR and the actual tunnel?"

Answer	No of answers	Percentage of people that mentioned the issue
VR lacked haptic feedback	8	53.3%
VR was blurry	3	20.0%
VR measurements were easier to take	2	13.3%
Working conditions in VR are better	2	13.3%
VR lacked collaboration aspect	2	13.3%
VR wall model covered too small area	2	13.3%
Switching between tools was easier in VR	2	13.3%
VR answer input system was inaccurate	2	13.3%
VR was more fun	1	6.7%
Dimensions were distorted in VR	1	6.7%
VR lacks world direction indicator	1	6.7%
VR can augment the real tunnel visit	1	6.7%
Real space reserved for VR was too small	1	6.7%
Measurement in the tunnel were easier	1	6.7%
Rock structure observations in real life are more accurate	1	6.7%
VR tools (Barton's comb) were harder to use	1	6.7%
VR can be accessed anytime	1	6.7%
VR scene is faster to access	1	6.7%
VR tools worked better (compass)	1	6.7%
Less distractions in VR	1	6.7%
VR had better instructions	1	6.7%
TOTAL answers	36	
No answer	5	33.3%

Table 24 Overall SUS score and learnability

Parameter	Usability	Learnability
MIN	55.00	37.50
MAX	90.00	100.00
MEAN	72.25	72.50
ST. DEV	10.54	17.01
MEDIAN	73.75	75.00
VARIANCE	111.12	289.47

Table 25 Correlation between the reported usability, learnability and the time required to finish the exercise (T2+T3)

User ID	**T1+T2 [min]**	**Usability [-]**	**T1+T2 [min]**	**Learnability [-]**
1	8.17	77.5	8.17	87.5
2	15.37	75.0	15.37	75.0
3	17.02	60.0	17.02	50.0
4	18.23	85.0	18.23	100.0
5	24.50	72.5	24.50	62.5
6	12.55	90.0	12.55	87.5
7	18.98	55.0	18.98	62.5
8	18.73	75.0	18.73	75.0
9	16.67	75.0	16.67	62.5
10	29.32	67.5	29.32	62.5
11	17.50	55.0	17.50	50.0
12	21.00	60.0	21.00	62.5
13	16.60	75.0	16.60	75.0
14	17.43	70.0	17.43	75.0
15	16.55	72.5	16.55	62.5
16	19.53	90.0	19.53	100.0
17	18.18	82.5	18.18	87.5
18	25.10	60.0	25.10	37.5
19	18.40	80.0	18.40	87.5
20	20.73	67.5	20.73	87.5
$r_{X,Y}$	-0.348		-0.379	
t-value	-1.574		-1.740	
p-value	0.132		0.098	
Significance level α	0.050		0.050	
Significance of the results	Insignificant		Insignificant	

Table 26 Preferred ways of learning rock wall mapping

Place	I prefer to learn tunnel mapping in:		I have learned more about tunnel mapping in:	
Virtual reality	3	15.00%	3	15.00%
The actual tunnel	11	55.00%	12	60.00%
Both	6	30.00%	4	20.00%
Neither	0	0.00%	1	5.00%
Total	20	100%	20	100%

Table 27 Reasons behind choosing a specific way of learning

Answer	No of answers	
VR should be an addition to the actual tunnel exercise	4	26.67%
Learning seems easier in reality	2	13.33%
VR allows for tunnel visits anytime	2	13.33%
VR does not correspond well to reality	2	13.33%
VR tools did not correspond well to reality	2	13.33%
It is easier to distinguish joint sets in reality	1	6.67%
The real visit allows for consultation with peers	1	6.67%
The real visit allows for consultation with the lecturer	1	6.67%
Tunnel visit is closer to theory from the lectures	1	6.67%
VR measurements were not accurate	1	6.67%
VR tools were easier to use	1	6.67%
TOTAL	15	100.0%
No answer	3	-

Table 28 Reasons behind why a specific way of learning allowed to gain more knowledge

Answer	No of answers	
The real visit allows for consultation with peers	3	27.27%
The real visit allows for consultation with the lecturer	2	18.18%
Conditions (lighting, temperature) were better in VR	1	9.09%
VR tools did not correspond well to real ones	1	9.09%
VR does not correspond well to reality	1	9.09%
VR allows saving time	1	9.09%
VR measurements were easier	1	9.09%
VR offered less distractions	1	9.09%
TOTAL	11	
No answer	10	

Appendix 5 Second experiment questionnaire

The Virtual Reality Experience Questionnaire

Name: ____ **Date:** ____________

Age: __________ **Gender:** Male[ ] Female[ ] Would rather not tell [ ]

4. Have you ever used Virtual Reality **before**?

No [ ] Yes, once or twice [ ] Yes, a few times [ ] Yes, many times [ ]

5. Have you ever done any tunnel mapping before?

No [ ] Yes, once or twice [ ] Yes, a few times [ ] Yes, many times [ ]

6. Do you play FPS games e.g. shooters on your computer/console?

Never or almost never [ ] Yes, monthly [ ] Yes, weekly[ ] Yes, daily [ ]

7. I experienced nausea during the virtual reality exercise
   1 is totally disagree and 5 is totally agree
   1 [ ] 2[ ] 3[ ] 4[ ] 5[ ]

   If you answered anything except 1 in question 3 please, answer the question 4
8. Has nausea influenced your capability to perform the measurements?
   1 is totally disagree and 5 is totally agree
   1 [ ] 2[ ] 3[ ] 4[ ] 5[ ]

SEE THE OTHER PAGE!

Answer the questions on a scale of 1 to 5, where **1 is totally disagree** and **5 is totally agree**

	1	2	3	4	5
1. I think that I would like to use VR frequently					
2. I found VR unnecessarily complex					
3. I thought VR was easy to use					
4. I think that I would need the support of a technical person to be able to use VR					
5. I found the various functions in VR were well integrated					
6. I thought there was too much inconsistency in VR					
7. I would imagine that most people would learn to use VR very quickly					
8. I found VR very cumbersome to use					
9. I felt very confident using VR					
10. I needed to learn a lot of things before I could get going with VR					

9. Which parts of the VR did you **like** the most? Name at least three

___

___

___

10. Which parts of the VR did you dislike the most? Name at least three

___

___

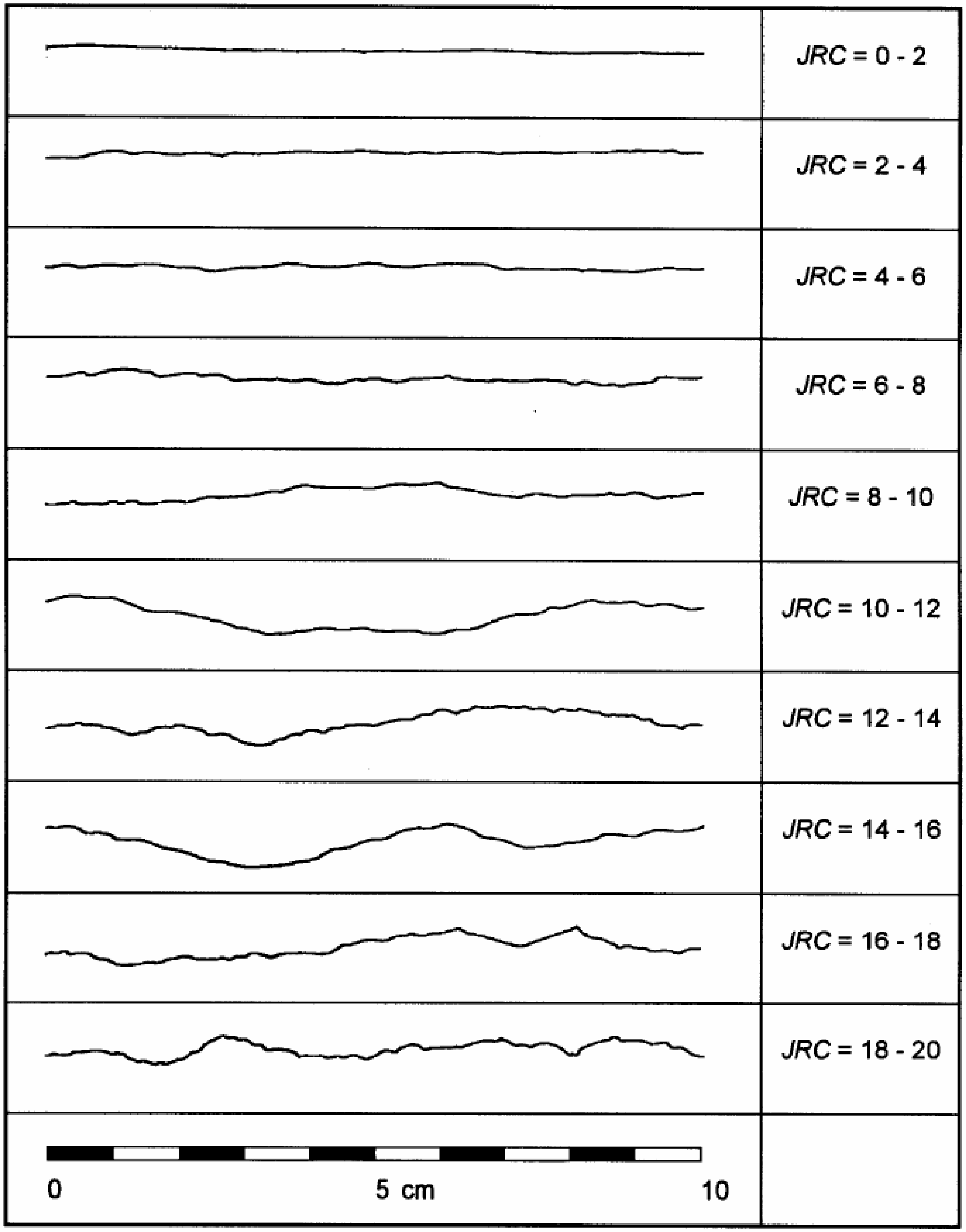
___

11. What can we change in order to improve our VR software? Are there any things in the User Interface that we should change? Any other comments?

___

___

Appendix 6 Joint Roughness Coefficient Chart



Source: Barton and Choubey, 1977